450390007

United States
Environmental Protection
Agency

Office of Air Quality
Planning and Standards
Research Triangle Park NC 27711

EPA-450/3-90-007
July 1991

Air

EPA

Guidance Document for Selecting Antiskid Materials Applied to Ice- and Snow-Covered Roadways

SM-X1

EPA-450/3-90-007

Guidance Document for Selecting Antiskid Materials Applied to Ice- and Snow-Covered Roadways

Emission Standards Division

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711
July 1991

DISCLAIMER

This report has been reviewed by the Emission Standards Division of the Office of Air Quality Planning and Standards, EPA, and approved for publication. Mention of trade names or commercial products is not intended to constitute endorsement or recommendation for use. Copies of this report are available through the Library Services Office (MD-35), U.S. Environmental Protection Agency, Research Triangle Park, NC 27711, or from National Technical Information Services, 5285 Port Royal Road, Springfield, VA 22161.

CONTENTS

Preface iii
Figures vii
Tables ix

1. Introduction 1-1
2. Current Practices for Skid Control 2-1
   2.1 Antiskid materials 2-1
   2.2 Application rates and procedures 2-13
   2.3 Removal techniques 2-25
3. Measurement Methods for Physical Properties 3-1
   3.1 Silt measurement methods 3-1
   3.2 Durability measurement methods 3-2
   3.3 Analysis methods for other properties 3-7
   3.4 Measurement methods for deicing chemicals 3-7
   3.5 Modifications to standard test methods 3-10
4. Selection Criteria 4-1
   4.1 Potential for dust emissions 4-1
   4.2 Effectiveness of antiskid materials 4-3
   4.3 Material durability 4-16
   4.4 Initial acceptability criteria 4-21
5. Materials Evaluation 5-1
   5.1 Origin of material samples 5-1
   5.2 Material properties 5-1
   5.3 Materials classification analysis 5-6
6. Simulated Traffic Tests 6-1
   6.1 Material selection 6-1
   6.2 Traffic tests 6-2
   6.3 Small scale experiments 6-17
   6.4 Data analysis 6-21
7. Conclusions and Recommendations 7-1
   7.1 Conclusions 7-1
   7.2 Final material selection criteria 7-3
   7.3 Recommendations 7-4
8. References 8-1

CONTENTS (continued)

Appendices

A. Survey procedures A-1
B. Bibliography B-1
C. Alternative skid control measures C-1
D. ASTM silt analysis methods D-1
E. ASTM method for the Los Angeles Abrasion test F-1
F. State derived aggregate durability tests F-1
G. ASTM Method E 384-89 for Vickers hardness G-1
H. ASTM Method E 534-86 for determination of percent insoluble matter in sodium chloride H-3
I. Cost considerations for antiskid materials I-1

FIGURES

Number		Page
1-1	Total particulate emission factor vs. average silt loading for an artificially loaded paved road.	1-2
1-2	Diagram of street surface/atmospheric exchange of particulate matter	1-4
4-1	Sieve analysis data of antiskid material in Helena parking lot	4-2
4-2	Total loading and silt loading vs. number of vehicle passes for artificially loaded paved road	4-4
4-3	Profiles of total particulate concentration for artificially loaded paved road	4-5
4-4	Increase in total surface loading vs. time after application of salt or sand	4-6
4-5	Increase in silt loading vs. time after application of salt or sand	4-7
4-6	TSP air quality impact of salt and sand application over time	4-8
4-7	Coefficient of friction (f) vs. number of wheel passes for four antiskid materials compared on an equal volume basis	4-10
4-8	Skid resistance of limestone material vs. percent +200 mesh silica	4-11
4-9	Average British portable skid number vs. rate of aggregate application for various antiskid materials (30°F)	4-13
4-10	Average British portable skid number vs. rate of aggregate application for various antiskid materials (0°F)	4-14
4-11	Average stopping distances determined on an ice track for various antiskid materials	4-15
4-12	Mineral wear rate vs. Vickers hardness for SiO_2 abrasive	4-18
5-1	Scatterplot of silt content vs. LA abrasion loss	5-13
5-2	Scatterplot of percent void fraction vs. particle shape index	5-15
5-3	Percent deviation from mean value by cluster type	5-17
6-1	MRI wheel passage machine	6-3
6-2	Percent moisture vs. equivalent vehicle passes for Samples 1-3	6-11
6-3	Percent moisture vs. equivalent vehicle passes for Samples 4 and 5	6-12
6-4	Percent moisture vs. equivalent vehicle passes for Samples 8 and 9	6-13
6-5	Percent silt (% < 75 μmP) content vs. equivalent vehicle passes for Samples 1, 1D, and 2	6-14

FIGURES (continued)

6-6 Percent silt (% < 75 μmP) content vs. equivalent vehicle passes for Samples 3, 4, and 5 6-15

6-7 Percent silt (% < 75 μmP) content vs. equivalent vehicle passes for Samples 8 and 9 6-16

6-8 Correlation of change in mass median particle diameter with LA abrasion loss 6-26

7-1 Decision "tree" for antiskid material selection 7-5

TABLES

Number		Page
2-1	Results of surveys of antiskid measures	2-2
2-2	Standard U.S. Screen Scales	2-6
2-3	Desirable characteristics of abrasives	2-7
2-4	Composition of water insolubles in rock salt	2-10
2-5	Annual average purity of rock salt, dry basis	2-10
2-6	Qualitative evaluation of chemicals and abrasives used in snow and ice control	2-12
2-7	Chemical and sand use	2-14
2-8	State snow and ice control materials use	2-17
2-9	Highway salt sales by U.S. members of the Salt Institute (1989)	2-21
2-10	Stormfighting guidelines of the Salt Institute	2-22
2-11	Guidelines for chemical application rates	2-23
3-1	Summary of instrumental methods of particle size analysis	3-3
3-2	Summary of test methods related to antiskid materials	3-8
3-3	Modifications to ASTM method C 131-89	3-11
3-4	Modifications to ASTM method C 131-89 for aggregate material < 2.36 Mm	3-12
3-5	Silt analysis procedures	3-15
3-6	Modifications to ASTM E 384-89 to incorporate fine aggregate materials	3-16
3-7	Modifications to ASTM E 534-86 to include calcium magnesium acetate (CMA)	3-18
4-1	Results of impact tests	4-10
4-2	Material specifications for Alaska tests	4-12
4-3	Average mineral wear for different abrasive types	4-17
4-4	Acceptability criteria for antiskid materials	4-21
5-1	Sample inventory	5-2
5-2	Applicable test methods for antiskid materials	5-5
5-3	Results of laboratory evaluation	5-7
5-4	Results of materials evaluation	5-9
5-5	Range percent values for modified ASTM methods	5-11
5-6	Linear correlation coefficients (r)—material properties	5-12
5-7	Breakdown of test materials by characteristic type	5-16
5-8	Summary statistics—material properties by characteristic cluster type	5-19
6-1	Antiskid materials exposed to simulated traffic	6-2

TABLES (continued)

6-2 Silt analysis procedures 6-6
6-3 Moisture analysis procedure 6-8
6-4 Sonic sieving procedure 6-9
6-5 Test track material balance 6-18
6-6 Particle size data for traffic test No. 6 (rock salt) 6-19
6-7 Results of chemical analyses for NaCl tests 6-19
6-8 Results of small scale experiments 6-22
6-9 Particle size data for small scale experiments 6-23
6-10 Mass median diameter (μmP) of abrasive samples tested on wheel passage machine 6-24
6-11 Linear correlation between MMD change and test material properties 6-24
6-12 Mass balance for rock salt (NaCl) tests 6-27
7-1 Revised selection criteria for antiskid abrasives 7-3

SECTION 1

INTRODUCTION

Several areas of the country which are in violation of the National Ambient Air Quality Standard for PM_{10} (airborne particles less than or equal to 10 μmA in diameter) have conducted studies to identify the sources of these emissions. One source of PM_{10} emissions that has been identified in several of these studies is the resuspension of antiskid material applied to active roadways.

Antiskid materials may consist of sand, stone, cinders, or other materials applied to the road surface to improve traction on snow- and ice-covered roadways. "Deicers," on the other hand, serve to restore the traction associated with the road surface itself.

Prior research has established a direct relationship between the loading of fines on a paved roadway and the PM_{10} emissions generated by vehicular traffic. In the initial study, a salt/sand spreader was used to load a test road with: (a) pulverized top soil for one test series; and (b) limestone gravel fines for a second test series (Cowherd et al., 1977). Exposure profiling was used to quantify emissions over periods of 30 to 60 min under controlled traffic conditions. The resulting relationship (Figure 1-1), between silt loading and the total particulate emission factor represents conditions that closely parallel the application and resuspension of antiskid materials consisting of insoluble abrasives.

The relationship between silt loading and PM_{10} emissions is reflected in the EPA-recommended PM_{10} emission factors for paved urban roads. This relationship was developed from a data base encompassing the results of tests conducted at eight sites ranging from a freeway to a rural town road. According to EPA Publication AP-42, the quantity of dust emissions from vehicle traffic on a paved roadway per vehicle kilometer of travel may be estimated using the following empirical expression (USEPA, 1985):

$$e = 2.28 \; x \left(\frac{sL}{0.5}\right)^{0.8} \qquad (1\text{-}1)$$

where:
- e = PM_{10} emission factor (g/VKT)
- L = total road surface dust loading (g/m^2)
- s = surface silt content (fraction of particles < 75 μm in physical diameter)

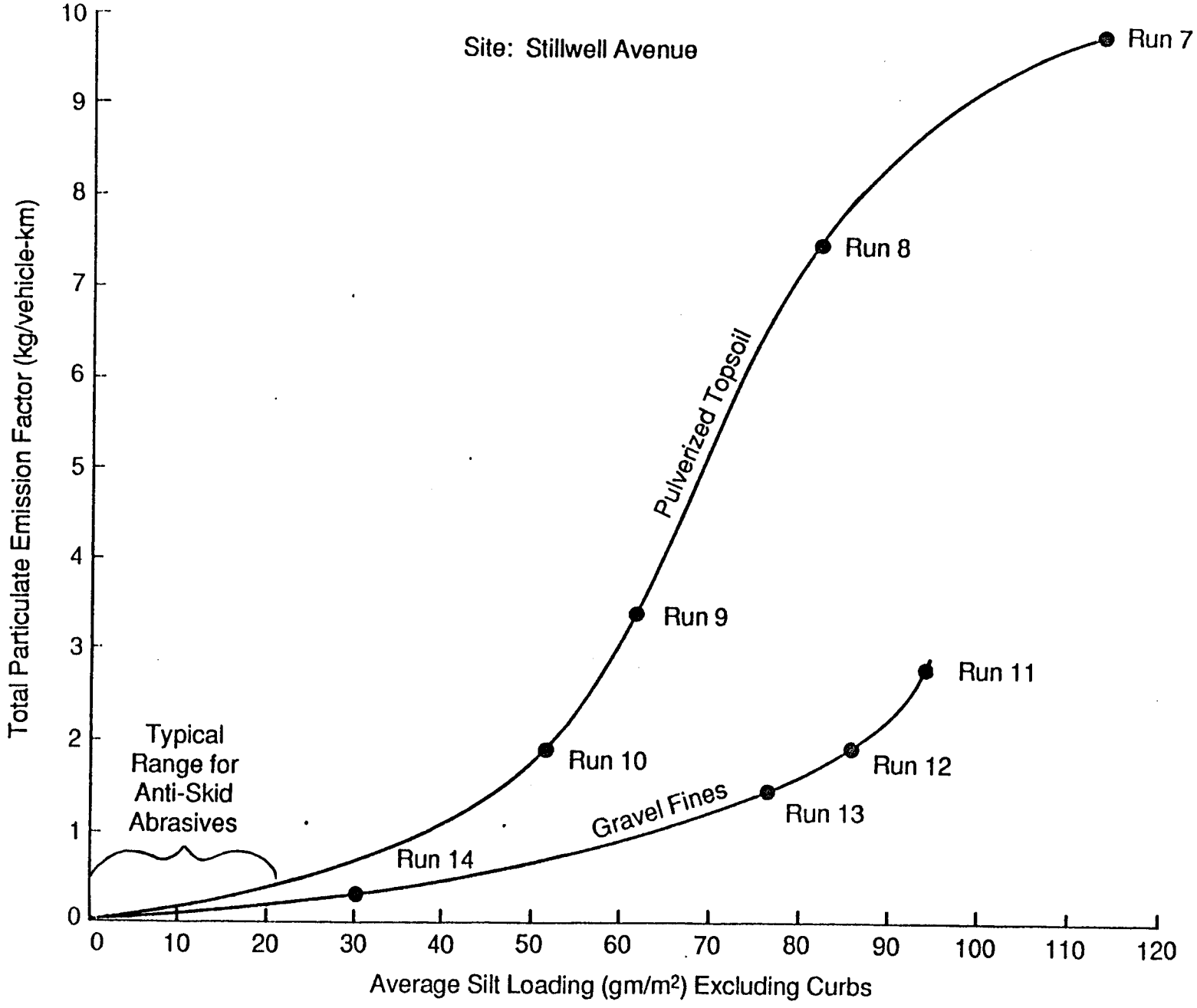


Figure 1-1. Total particulate emission factor vs. average silt loading for an artificially loaded paved road

The total loading (excluding litter) is measured by sweeping and vacuuming lateral strips of known area from each active travel lane. The silt fraction is determined by measuring the proportion of loose dry road dust that passes a 200 mesh screen, using a modified version of ASTM C 136 method. Silt loading is the product of total loading and silt content.

Recently, in the absence of specific emission test results for antiskid materials, PM_{10} emission factors from sanding and salting were estimated as a "gap filling" exercise (Grelinger et al., 1988). The emission factor for sanding assumed that all of the PM_{10} content of typical road sand would be suspended. In the case of salting, the emission factor was based on the assumption that: (a) 5% of the salt takes the form of a dried film on the pavement; and (b) 10% of the film is liberated as PM_{10} particles. Because of the uncertainties in these underlying assumptions, a low quality rating (E) was assigned to the estimated emission factors.

It is clear from Equation (1-1) that techniques for controlling PM_{10} emissions resulting from antiskid materials should be aimed at minimizing silt loading on the traveled portion of the roadway (Figure 1-2). Specifically, reduced silt loadings may be expected to result from snow/ice control programs that encompass improvements in three areas: the properties of antiskid materials applied; the application protocols and procedures; and the procedures for removal of the antiskid material from roadways. For example, emission reductions may result from: substitution of different deicing materials for salt and the use of antiskid materials that have been tested for durability and silt content; lower application rates; and application of material to fewer roadways. Removal methods focus on the following roadway cleaning procedures: broom sweeping (wet or dry), vacuuming, or water flushing. Water flushing (during periods with ambient temperatures above freezing) followed by broom sweeping has proven to be most effective in capturing silt-sized particles present in paved road surface material (Cowherd et al., 1988).

Local, state, and regional air pollution control agencies have requested information on how to identify an appropriate antiskid material that is both durable and effective and that produces fewer PM_{10} emissions. Thus the primary purpose of this study is to provide guidance on methods to determine: (a) the physical properties and durability of antiskid material selected for use on ice- and snow-covered roadways (see Figure 7-1); and (b) criteria for defining the elements of an effective PM_{10} emission control strategy associated with use of antiskid materials (see Table 7-1).

To meet the above objectives, the program was conducted in two phases consisting of: (a) a literature search, telephone survey, and engineering analysis; and (b) a laboratory evaluation of typical antiskid materials. Phase 1 of the study was intended to collect sufficient background information to derive preliminary selection criteria for antiskid materials based on existing data. The second phase of the program involved

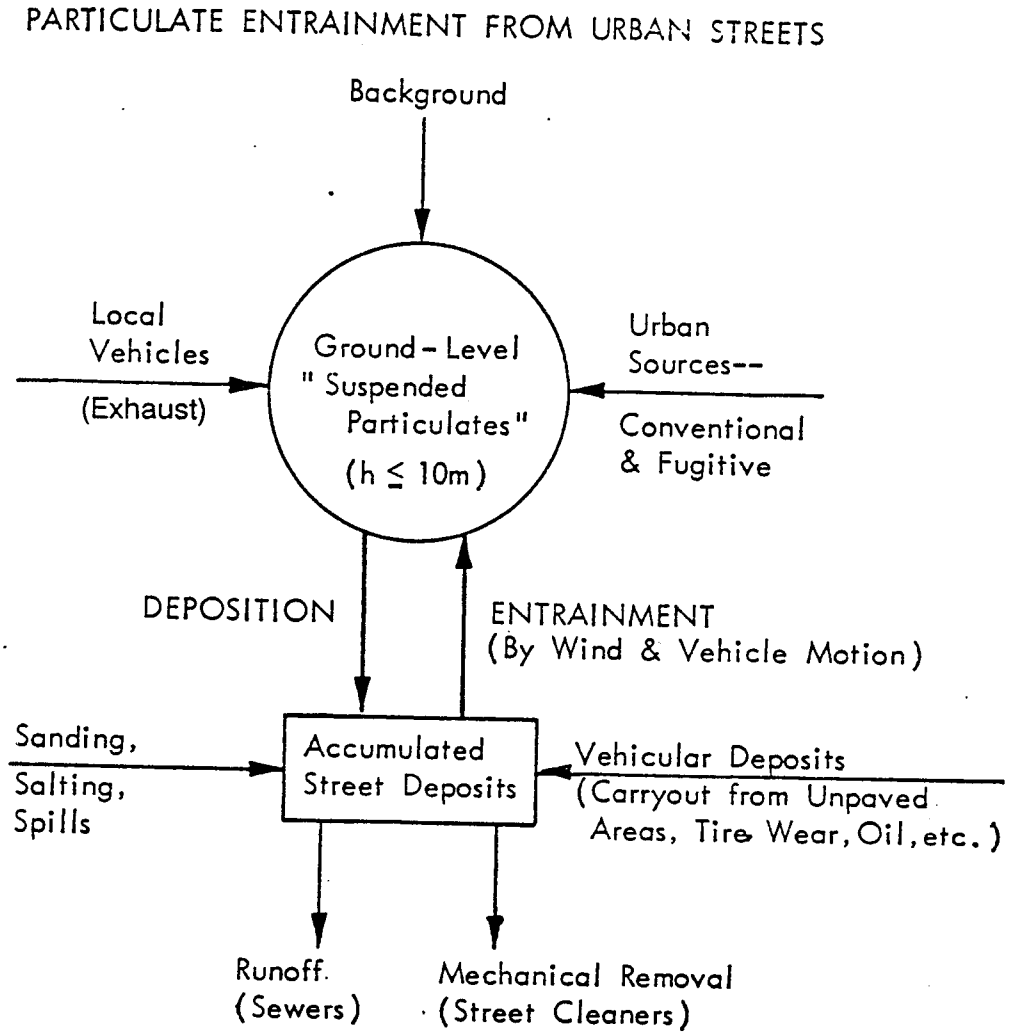


Figure 1-2. Diagram of street surface/atmospheric exchange of particulate matter.

an experimental study to: (a) determine the physical properties of typical antiskid materials; (b) conduct suitable tests of selected materials to determine their potential for the generation of PM_{10}; and (c) refine the material selection criteria developed previously. Each phase of the program is discussed in Sections 2 through 8 below.

Two survey methods were used in this study to gather the information needed to meet the study objectives. First, an extensive literature survey was performed by on-line accession of computerized informational data bases. Then a direct telephone survey was targeted to states and municipalities known to be concerned with antiskid control was performed. The methodologies for these surveys are described in detail in Appendix A.

For the purpose of describing abrasive materials, the following definitions will apply:

1. Antiskid material: materials such as sand, stone, cinders, etc., spread on an ice or snow-covered roadway to improve traction.

2. Deicing chemical: salts or similar compounds that control snow and ice by preventing the formation of ice films, weakening the bond between snow and the road surface, and/or by melting snow.

3. Antiskid abrasive: solid aggregate materials such as natural sand, manufactured sand, or cinders applied to a road surface to provide an immediate increase in skid resistance.

4. Sand: shall mean either "fine aggregate" or "manufactured sand," according to American Society for Testing and Materials definitions which follow.

5. Fine aggregate: aggregate passing the 3/8-in sieve and almost entirely passing the No. 4 (4.75 mm) sieve and predominantly retained on the No. 200 (75 μm) sieve.

6. Manufactured sand: the fine material resulting from the crushing and classification by screening, or otherwise, of rock, gravel, or blast furnace slag.

The organization of this document by section is as follows:

- Section 2 describes current practices for skid control.

- Section 3 evaluates measurement methods for the physical properties of antiskid materials.

- Section 4 develops the rationale for selection of effective antiskid materials based on available literature.
- Section 5 presents the physical and chemical properties of typical antiskid materials obtained from local sources and state regulatory agencies.
- Section 6 provides the results of the experimental testing program.
- Section 7 presents the conclusions and recommendations derived from this study.
- Section 8 lists the references used in the study.

SECTION 2

CURRENT PRACTICES FOR SKID CONTROL

Abrasives and deicing chemicals are the most commonly used antiskid materials. These materials prevent formation of ice, melt ice that has formed; prevent buildup of snowpack, or create a higher coefficient of friction for vehicle tires.

Some abrasives used include sand and cinders which provide a gritty surface on snow and ice-covered roadways. Deicing chemicals are freezing point depressants that melt ice and snow to achieve a wet surface to be maintained until drying occurs. The two most commonly used deicing chemicals are rock salt (94% to 99% sodium chloride, NaCl) and calcium chloride ($CaCl_2$).

Eleven states and municipalities were surveyed by telephone (some with multiple contacts) to gather information on current practices for skid control, especially as related to impact on dust production. In addition, a comprehensive literature review was performed to document the use and effectiveness of abrasives, chemicals and other antiskid materials, and methods. The survey procedures used in the program are outlined in Appendix A with a bibliography of documents reviewed but not actually cited in this report contained in Appendix B. Appendix C provides a brief overview of other techniques potentially useful for ice and snow control.

This section documents results from the literature review, a review of results from a survey undertaken by the South Dakota Department of Transportation and the telephone survey. In this section the word "salt" applies only to rock salt; other chemical salts such as calcium chloride are referred to by their chemical name.

2.1 ANTISKID MATERIALS

2.1.1 Survey Results

Table 2-1 presents a summary of the antiskid materials used by the two cities and 26 states who were surveyed by telephone and by the South Dakota questionnaire. Almost all state and local agencies used rock salt and sand. One state, New Jersey, used rock salt exclusively, stating that it was required for motorist safety and that sand clogged drainage inlets. Many states mixed sand and salt in various proportions. Sand was never used in urban areas exclusively. Higher proportions of salt to sand were used in urban areas while lower proportions were applied in rural areas where traffic intensities

TABLE 2-1. RESULTS OF SURVEYS OF ANTISKID MEASURES

State/city	Types of material	Cost ($)	Abrasives (maximum % < 200 mesh)	Sieving method	Comments
Indianapolis	Salt $CaCl_2$ (32%) Sand	27.05/ton salt 0.38/gal $CaCl_2$ 2.00/ton sand	NS	Indiana DOT Section 903 of highway manual	Salt/sand is used in outlying areas only; only salt applied to city roads since sand clogs sewers.
Minneapolis	Salt Portland cement Sand	25.00/ton salt	2	ASTM C136	Washed sand must drain 12 h; sand must be free of organic impurities and colorplate < No. 2; maximum 2.5% shale, strength ratio of 1.00+ as measured by ASTM C87-83.
Alaska	Salt, sand, urea, "Quicksalt," crushed stone	NS	2	NS	Durability—based on shaker test from Washington state.
Connecticut	Salt $CaCl_2$ Screened pit Crushed quarry Washed stone sand	34.79/ton salt 98.04/ton $CaCl_2$ 8.43/yd^3 sand	5	AASHTO T-11	"Clean, hard, and durable" sand. No clay, dirt, loam, or frozen lumps. Washed sand must sit for 24 h.
Delaware	Washed concrete sand	NS	4	NS	—
Idaho	Screened pit Crushed pit Crushed quarry Screened cinders Quarry cinders	NS NS NS NS NS	No specification	NS	—
Indiana	Sand Slag Cinders	NS NS NS	3, 6, or 7, dependent on sand class	NS	—
Colorado	Salt Sand	NS NS	No specification	NS	—
Iowa	Screened pit	NS	3	NS	No crushed material used.

(continued)

TABLE 2-1 (continued)

State/city	Types of material	Cost ($)	Abrasives (maximum % < 200 mesh)	Sieving method	Comments
Maine	Screened pit Crushed pit	NS NS	No specification	NS	—
Massachusetts	Screened pit Washed pit	NS NS	3	NS	—
Michigan	Screened pit Screened/washed pit	NS NS	3	NS	No crushed stone; < 7% loss by washing; similar to 2 NS materials in aggregate table. Fineness modulus 2.50 to 3.35.
Minnesota	Screened pit sand	NS	NS	NS	—
Montana	Pit run Screened pit Crushed pit Maintenance aggregate (> ½")	NS NS NS NS	10 < 100 mesh — — 10	NS	Unit weight tested for, but no specifications.
Nebraska	Screened pit Boiler slag	NS NS	6	NS	No crushed material.
Nevada	Screened pit	NS	8	NS	—
New Hampshire	Screened pit Washed sand	NS NS	12 < 4 mesh	NS	Must be washed; sharp "feel" desirable.
New Jersey	Salt				No sand used because of clogging of inlets and drainage, and motorist safety.
New York	Pit run Screened pit Crushed pit Crushed quarry Iron ore tailings Crushed slag Crushed cinders	4.25/ton sand NS NS NS NS NS NS	5	New York DOT 703-1P 703-2P	Must be free of too much clay, loam, etc.; particles must not degrade in service and must visually contrast with ice/snow.

(continued)

TABLE 2-1 (continued)

State/city	Types of material	Cost ($)	Abrasives (maximum % < 200 mesh)	Sieving method	Comments
Ohio	Screened pit	NS	30 < 50 mesh	NS	—
	Crushed quarry	NS			
	Cinders	NS			
	Blast furnace agg	NS			
	Slag	NS			
Oregon	Crushed quarry	NS	1	OSHD 101	Cubical aggregate specified.
Utah	NS	NS	10 or 15	AASHTO T-11	Portion through No. 40 sieve shall be nonplastic by AASHTO HTO T-90; sand equivalent 80+ (UDOT 8-938); AASHTO T-19 loose weight.
Vermont	Screened pit	NS	10	NS	—
	Crushed quarry	NS			
	Pit run	NS			
Washington	Crushed pit	NS	4 or 5	NS	Minimum of 1 face for aggregate. Low fines present fewer problems with water retention and plugging.
	Crushed quarry	NS			
	Pit run	NS			
	Screened pit	NS			
West Virginia	Crushed stone	NS	8 < 100 mesh	NS	—
	Boiled slag	NS	5 < 100 mesh	NS	
Wisconsin	Pit run	NS	5	NS	—
	Screened pit	NS			
Wyoming	Screened pit	NS	15	NS	Plastic index < 6. Free of organic material.
	Crushed pit	NS			

NS = Not specified.

are less. Agencies typically reported their selection of antiskid materials was based on what was available (and, presumably, at reasonable cost).

2.1.2 Abrasive Usage and Specification

As stated in Section 1, the potential for dust emissions from abrasives can be estimated from the silt fraction (i.e., percentage that passes a No. 200 mesh or < 74)m diameter). Table 2-2 compares U.S. standard mesh sizes and gives the nominal aperture widths. The entire PM_{10} fraction contained in the silt of the applied abrasive can be assumed to become airborne. Ratios of PM_{10}/PM_{75} for common abrasives have not been reported in the literature. However, an analysis of naturally-occurring, western sandy soils produces an average ratio of 0.0026. This ratio times the silt fraction times the quantity of sand applied gives an estimated 7.5 g/metric ton (0.018 lb/ton) emission factor for road sanding developed by Grelinger (1988).

Another measure of dust potential is the hardness or durability of the abrasive material. Soft particles tend to crumble as they are abraded between vehicle tires and pavement, while hard, angular particles tend to remain integral.

Sand is the most common abrasive applied to roadways. It is a cheap commodity that is taken from pits, quarries, rivers and beaches. Sand sources are often close to roadways, reducing transportation costs. Some states maintain their own sources for road sand. Abrasives such as sand not only produce initial surface friction, but also break up ice or packed snow as vehicles travel over the roads.

"Good" abrasives are described by Keyser (1973) as having "resistance to degradation, angular shape, dark color and uniform grain size." He also concludes that fines passing a No. 50 sieve contributes almost nothing to skid resistance. Tests reported by Hegmon and Meyer (1968) indicate that the highest coefficients of friction are produced by particles between the No. 8 and the No. 16 sizes, and that a slight improvement in skid resistance is realized when particles passing a No. 50 sieve are removed. Table 2-3 provides desirable characteristics of antiskid abrasives (Schneider, 1959).

Most agencies specify a top size of 3/8 in diameter for abrasives, but the maximum fine particle (passing a 200 mesh or < 75 μm diameter) specification for sand ranges from 2% to 15%. Some agencies reported that no specifications for fines are used, but sometimes the sand must be washed.

Certain agencies specify "clean, hard, and durable" material with a "sharp" feel, but most do not have quantitative specifications for hardness, durability, or number of faces. One state reported the use of the Los Angeles abrasion test by cities, and said the same

TABLE 2-2. STANDARD U.S. SCREEN SCALES (SHEEHY, 1968)

Nominal aperture width			Nominal aperture width		
Microns	Inches	U.S. standard	Microns	Inches	U.S. standard
1	.00004	12,500	297	.0117	50
2.5	.0001	5,000	350	.0138	45
5	.0002	2,500	420	.0165	40
10	.0004	1,250	500	.0197	35
20	.0008	625	590	.0232	30
37	.0014	400	710	.0280	25
44	.0017	325	840	.0331	20
53	.0021	270	1,000	.0394	18
62	.0024	230	1,190	.0469	16
74	.0029	200	1,410	.0555	14
88	.0035	170	1,680	.0661	12
105	.0041	140	2,000	.0787	10
125	.0049	120	2,380	.0937	8
149	.0059	100	2,830	.111	7
177	.0070	80	3,360	.132	6
210	.0083	70	4,000	.157	5
250	.0098	60	4,760	.187	4

TABLE 2-3. DESIRABLE CHARACTERISTICS OF ABRASIVES (SCHNEIDER, 1959)

Characteristic	Rationale
Great resistance to compression, crushing, impact, and grinding	Resist degradation under the action of traffic; could be recovered in spring
Angular shape	Greater stability; prevent its being blown away
Darkish color	Absorbs heat to melt itself into the surface of ice
Uniform grain size	Uniform spreading pattern; less likely to damage equipment

pits tested also supply sand for both local and state highways. Occasionally sand rejected for use in concrete or mortar is used for road antiskid material.

Cinders (steel and silver slag; boiler bottom ash) are used by several agencies. One state commented that cinders are the best abrasive since they are black and fine, and absorb sunlight to melt ice and snow. But one agency said they are not able to use copper slag because of heavy metal content. Another said that if citizens can "see" the deposited material, they credit the highway department with "doing their job." An additional comment was that this precludes the use of "white" limestone that cannot be seen on snow and ice.

A study done by Eck (1986) reported that four tested abrasives—boiler house cinders, coke cinders, sand and stone—are essentially the same in effectiveness and that selection should be based on cost factors. Eck also reported that one state used sawdust as an antiskid material and New York reported using iron ore tailings. Montana reported they did not reuse reclaimed sand from roads because of the size gradation requirement, but another state said that up to 10% of reclaimed sand can be used.

Objections to abrasive use found in the literature search include:

1. Cinders are quite bulky and frequently nonuniform in size, causing problems with delivery systems.

2. Cinders are usually acidic and can cause corrosion.

3. Cinders are easily blown away because of their light weight.

4. Cinders often contain significant levels of toxic heavy metals.

5. Both cinders and sand are deposited in catch basins and drain conduits, requiring laborious efforts to remove them.

6. Coarse sand (> 3/8 in) can break windshields by being thrown into the air by tires.

7. Sand smothers roadside vegetation.

8. Sand causes silt buildup in ponds and lakes.

9. All abrasives form a thick ice mat that will melt near warm spots such as manholes, causing deep holes and ruts that are traffic hazards.

10. All abrasives require heavy application amounts (in comparison with deicing chemicals) to achieve good skid resistance.

11. All abrasives should be cleaned from roadways after storm periods.

2.1.3 Deicing Chemicals

The potential for dust emissions from deicing chemicals is based on the amount and type of chemical that can be suspended by tire and wind action. Deicing chemicals form a liquid solution as ice is melted. Much of this water/chemical solution will run off the roadway, but some will be sprayed into the air by traffic. Evaporated droplets may constitute a source of airborne particulates, but a larger source is likely to be the film of solid residue left on the pavement surface upon evaporation of any remaining water/chemical solution. This dry film residue will be a source of suspended particulate upon contact with vehicle tires and wind.

Rock salt, the most commonly used deicing chemical, achieves good skid control results with far less quantity than abrasives. It is also the cheapest deicing chemical available, but does cause corrosion of vehicles and metal structures. Major rock salt deposits are found in New York, Michigan, Kansas, Texas, and Louisiana. Solar salt ponds on the Great Salt Lake also supply some road deicing salt. Salt used in the coastal state of Maine, however, comes from Spain and Canada. Salt used in Alaska is shipped from Seattle.

Much of the sodium chloride in rock salt is believed to wash off the roadway since salt is very soluble in water. Even some suspended impurities in rock salt are likely to run off with the melted snow/ice. However, some fraction of sodium chloride and the insoluble impurities in rock salt are likely to be deposited on the pavement upon roadway drying, to be suspended later by tire or wind action. Few data were found in the literature concerning quantities of sodium chloride or insoluble matter left on roadways after

deposition of rock salt, or the size fraction of this material when suspended. One study (Keyser, 1981) claimed that an advantage of rock salt was that it "freezes dry on pavement surface."

An estimate of PM_{10} emissions from the sodium chloride in rock salt has been reported as 10 lb/ton of salt applied, based on an estimate of 5% of the salt remaining as a dried film on the road pavement, and 10% of this film being suspended as PM_{10} (Grelinger et al., 1988). No field data were available for validation of this estimate.

The sodium chloride content is about 99% for rock salt mined in Louisiana, 98% in New York and Michigan, and 94% to 98% in Kansas. Proportions of the remaining natural impurities found in rock salt are shown in Table 2-4. Table 2-5 shows that small particles of rock salt are richer in NaCl than larger particles.

Calcium sulfate, the major impurity in rock salt, is present as small lath-like crystals or crystal fragments of 100 μm average length which are slowly and difficultly soluble. Highly dissolved sulfate occurs with fine grinding and long dissolving time (> 30 min) of rock salt (Kaufmann, 1968). Both of these conditions are satisfied with salting of roadways.

Other impurities in rock salt, including silica, alumina, ferric iron, and dolomite, are not water soluble. Many quartz grains are very small (< 10 μm in diameter). It is possible that only the truly insoluble impurities left on roadways after runoff and evaporation will constitute a significant source of suspended particulate. Table 2-5 shows how the purity of rock salt is dependent on its source.

Additional impurities are added by salt mines for anticaking properties. Chromates, phosphates, and similar compounds may also be added to rock salt as possible corrosion inhibitors.

Calcium chloride is the second most common deicing chemical. It is often mixed with sand and rock salt, either as a pellet or as a liquid, to produce a more effective deicing mixture at low ambient temperatures. The eutectic temperature[1] of calcium chloride is -55°C (-67°F), considerably lower than that of sodium chloride. Connecticut reported that calcium chloride is applied only in watershed areas as three parts salt and one part calcium chloride. Indianapolis reported 5% of calcium chloride is mixed with 95% salt for application to city streets.

One report noted that calcium chloride added to rock salt produced less visible salt residue both on the pavement and shoulders. The Legislative Research Council of Massachusetts (1965) stated that "this salt residue is apparent on the pavement for several days after a storm; it was, as late as spring, still obvious on the shoulders and

---

[1]Eutectic temperature is the lowest point at which equilibrium is achieved between the solid and liquid phases.

TABLE 2-4. COMPOSITION OF WATER INSOLUBLES IN ROCK SALT (PERCENT BY WEIGHT)

	Avery Island, Louisiana	Detroit, Michigan	Retsof, New York	Kansas
Quartz (silica), SiO_2	2.56	3.06	8.61	1.4
Iron oxide, Fe_2O_3	0.12	0.73	3.04	0.7
Magnesium carbonate, $MgCO_3$	0.61	1.71	4.14	—
Calcium carbonate, $CaCO_3$	Trace	6.37	2.50	2.4
Calcium sulfate, $CaSO_4$	96.66	86.85	81.16	94.5
Other				1.0
Total	100	100	100	100

Reference: Kaufmann (1968).

TABLE 2-5. ANNUAL AVERAGE PURITY OF ROCK SALT, DRY BASIS (PERCENT BY WEIGHT)[a]

Size[b]	Detroit, Michigan (12-year average)	Retsof, New York (14-year average)	Avery Island, Louisiana (representative composite)
No. 2	96.705	97.658	99.073
No. 1	97.388	98.101	99.094
CC	98.193	98.320	99.144 (A size)
FC	98.212	98.325	99.227 (C size)

[a] Reference: Kaufmann (1968).

[b] No. 2 = 0.42-0.50 in; No. 1 = 0.285-0.42 in; CC = 0.075-0.285 in; FC = < 0.075 in.

mall along the pavement edge in the other two sections. It is assumed that it was because of the use of calcium chloride that very little of this salt recrystallization was noted in the chemical mix test section."

Prilled urea and Quicksalt® (a reduced corrosion deicer) were the other two chemicals found to be used by agencies during the telephone survey. Both were used in Alaska for specialized purposes. The urea was obtained from a plant on the Kenai peninsula and shipping costs were presumably less than the shipping costs of salt from Seattle. The literature produced names of other chemicals used for roadway deicing, and these included liquid chemicals such as ethylene glycol, propylene glycol, and alcohols which would not produce any particulate emissions. These are discussed further in Appendix C.

Objections to common chloride salt deicing chemicals include:

1. Vehicle bodies and bridges are corroded.
2. Concrete surfaces deteriorate.
3. Vegetation is damaged.
4. Water supplies are contaminated.

2.1.4 Mixtures of Abrasives and Chemicals

The most common deicing mixtures are those of rock salt, sand, and calcium chloride. Table 2-6 presents a qualitative evaluation of chemicals and abrasives used for snow and ice control (Keyser, 1981). Sand is almost never applied by itself, but is mixed with a minimum of 5% rock salt to keep moisture in the sand from freezing. If melting action is desired, higher concentrations of salt are used. Salt and sand are usually premixed before a particular storm is forecast and left to set and cure for "better" action.

During the winter of 1988/1989, a 10% salt/90% sand mixture was tried in Denver, Colorado area, but the telephone responder said this mixture did not give good performance, so they have returned to an 18% salt/82% sand mixture. In Maine, 30 to 110 lb of rock salt are mixed per cubic yard of sand. In Connecticut, 300 lb of salt are mixed with 1,264 lb of sand for a 2-lane mile application on multilane systems. Eck (1986) reported, "the overall mean quantity of chemical used per cubic yard of abrasive is 225 lb..."

Salt cannot be used in very cold temperatures because its eutectic temperature is -21.1°C (-5.8°F). Addition of calcium chloride with a much lower eutectic temperature of -55°C (-67°F) makes a mixture able to melt snow and ice at lower temperatures and is also believed to make the mixture "stick better" to pavement. The residue of calcium chloride has been reported to provide "sufficient concentration to prevent ice bonding for up to 6 days after treatment" (Transportation Research Board, 1974 and 1984).

TABLE 2-6. QUALITATIVE EVALUATION OF CHEMICALS AND ABRASIVES USED IN SNOW AND ICE CONTROL (KEYSER, 1981)

Material	Main purpose	Suitability for use	Principal advantages	Principal disadvantages
Sodium chloride (rock salt), NaCl	To melt snow and ice.	Very effective when the temperature is above −3.8°C; effective between −3.8° and −9.5°C; marginal between −9.5° and −12.3°C; and not effective below −12.3°C.	Provides immediate traction. Salt particles bore, penetrate, and undercut the ice layer. Freezes dry on pavement surface. Low cost.	Low rate of solution. Ineffective at very low temperatures.
Calcium chloride, $CaCl_2$	To melt snow and ice.	Normally used when the temperature is below −12.3°C; effective down to −29.1°C; marginal between −29.1° and −34.7°C; and not effective below −34.7°C.	High rate of solution. Liberates heat on going into solution. Effective at low temperatures.	High cost. Melting action could take place at the ice surface. Pavements remain wet.
Mixtures of NaCl and $CaCl_2$	To melt snow and ice.	In cold weather, down to −17.9°C when snow and ice must be melted in a short time.	High rate of solution. Effective at low temperatures. Chemical more stable on the road.	High cost. Pavement stays wet longer than with $CaCl_2$.
Mixtures of abrasives and salt; abrasives treated with salt	To increase the sliding friction immediately.	In very cold weather, when salt is not effective or where clean plowing is impossible if immediate protection is necessary.	Free-flowing material. No freezing of stockpiles. Abrasives more stable on the road. Quick anchoring of abrasive to the road. Improve skid resistance immediately.	Creates spring cleanup problems. Does not remove ice or snow which causes slipperiness. May damage vehicles traveling at high speed.
Abrasives	To increase sliding friction immediately.		Improve skid resistance immediately.	As listed for other abrasives. Easily brushed off the road by tires.

2.2 APPLICATION RATES AND PROCEDURES

The U.S. Transportation Research Board (TRB) has twice printed the manual on "Minimizing Deicing Chemical Use" (1974 and 1984) that acknowledges that application rates are highly dependent on several factors. These include:

1. Level of service required.
2. Weather conditions and their change with time.
3. State and characteristics of chemicals used.
4. Time of application.
5. Traffic density at time of, and subsequent to, chemical application.
6. Topography and the type of road surface.

Table 2-7 presents a summary of chemical and sand use and application rates for 27 states, four Canadian provinces, and certain toll roads, counties, and cities published in 1974. The most comprehensive survey of deicing chemical and abrasive usage in the U.S. was collected by the Salt Institute (1984) for two winters in the early 1980s. Data collected in this survey are summarized in Table 2-8. Finally, highway salt sales by members of the Salt Institute are presented for 12 yr in Table 2-9 (Salt Institute, 1989).

Rock salt is applied routinely in cities with high traffic volumes, on icy spots such as hills and entrances to intersections, or where storm sewers are located. The telephone survey found application rates of 350 lb/lane-mile for Maine and 432 lb/2-lane mile in Connecticut for multilane systems with high traffic intensity.

A salt/sand mixture (18% rock salt, 88% sand by volume) applied at 300 lb/lane-mile is recommended in the Denver, Colorado area, but Colorado sand trucks do not have control levers for measured application intensities. Table 2-10 illustrates the recommended salting/sanding rates of the Salt Institute (1986).

Recommended rates of sand application found in the literature and phone survey ranged from .5 to 2 ton/lane mile. Maine applies a mostly sand mixture (30 to 110 lb of salt/1 yd^3 of sand) at 1 yd^3/lane mile. Connecticut reported the application of 300 lb of salt mixed with 1,264 lb of sand for a 2-lane mile application on multilane systems. Eck (1986) reported that the overall mean quantity of chemical used per cubic yard of abrasives is 225 lb, with Canadian usage appreciably higher at a mean of 335 lb. The chemicals used for these means were not given. [The conversion factor from cubic yards ofsand to tons is approximately 1.3.] Finally, the American Association of State Highway and Transportation Officials have published guidelines on the use of antiskid materials based on road and environmental conditions. These are shown in Table 2-11 (AASHTO, 1976).

To minimize deicing chemical use for environmental reasons, the Transportation Research Board (1974 and 1984) reports that agencies use liquid chemicals such as calcium chloride applied to rock salt, control application rates using calibrated spreaders,

TABLE 2-7. CHEMICAL AND SAND USE (TRANSPORTATION RESEARCH BOARD, 1974)

Agency	Year	NaCl (tons)	$CaCl_2$ (tons)	Sand (tons)	Other	Tons/lane mile	Application rates
		Annual totals					
STATES							
California	69/70	22,000					400 to 600 lb/mile on ice and compacted snow
	72/73	31,000					
Connecticut	72/73	87,600					
Idaho		8,000					400 lb/2-lane mile
Illinois	69/70	309,900	5,480				500 lb/2-lane mile
	70/71	256,411	3,380				
	71/72	280,930	3,390				
Kansas							500 to 1,000 lb/2-lane mile of 3:1 NaCl-$CaCl_2$; abrasives with 10% to 15% salt at 1,500 lb/mile
Maine	69/70	74,846				19.4	
	70/71	88,817				23.0	
	71/72	85,692				22.2	
Massachusetts	70/71	172,000		208,000	36,000		
	71/72	196,000		195,000	36,000		
	72/73	127,000		116,000	26,000		
Minnesota	69/70	172,720	2,906				600 to 800 lb/lane mile sand-salt; 400 to 500 lb/lane mile salt
	70/71	148,712	2,367			4.27	
	71/72	116,664	1,381	283,552		10.38	
Missouri	69/70	76,765	5,942				400 lb/2-lane mile (maximum)
	70/71	60,709	5,069				
	71/72	68,837	4,456				
Montana		2,850	45				100 to 300 lb/lane mile
Nebraska	72/73	18,000	800				200 to 500 lb/2-lane mile
Nevada							0.5 yd^3/2-lane mile
New Hampshire	69/70	153,742				19.5	
	70/71	144,982				18.3	
	71/72	157,238				19.8	
	72/73	96,983				12.2	
New Jersey		35,000	8,000				150 to 500 lb/lane mile
New York	69/70	192,384	2,285				200 to 600 lb/2-lane mile
	70/71	205,744	2,535				
	71/72	315,000	4,920			9.0	
North Dakota	70	4,800	1,000		32,000		
	71	4,100	1,375		17,000		
	72	4,000	650		174,000		
Ohio	69/70	510,000	2,600			12.7	
	70/71	470,000	2,300			11.7	
	71/72	424,000	3,000			10.6	

(continued)

TABLE 2-7 (continued)

Agency	Year	NaCl (tons)	$CaCl_2$ (tons)	Sand (tons)	Other	Tons/lane mile	Application rates
		Annual totals					
Oregon	69/70	810	180				
	70/71	710	260				
	71/72	720	None				
Pennsylvania	69/70	565,750	26,500				400 lb/lane mile max.
	70/71	738,800	31,100				60 to 80 lb/Type 1
	71/72	652,500	29,550				$CaCl_2$/ton sand
South Dakota	71	1,536	323	40,507			300 to 500 lb/2-lane mile
	72	1,890	368	43,400			
	73	2,804	380	46,400			
Vermont	69/70	110,000				21.1	300 to 800 lb/2-lane mile;
	70/71	88,000				16.3	546 lb/2-lane mile (average)
	71/72	97,000				17.6	
	72/73	88,260				16.0	
Virginia	69/70	56,097	22,211	252,568			
	70/71	66,243	18,987	223,028			
	71/72	44,518	9,151	112,573			
Washington	70/71	7,051					25° to 32°F: 200 to 250 lb/lane
	71/72	15,251					mile NaCl; 10° to 25°F: 250 to
	72/73	16,665					300 lb/lane mile 3:1 NaCl-$CaCl_2$;
							< 10°F: 350 to 450 lb/lane mile
							$CaCl_2$ flake or 300 to 375 lb/lane
							mile $CaCl_2$ pellet
West Virginia	69/70	152,453	10,045				500 to 600 lb/mile
	70/71	148,570	7,325				
	71/72	112,244	2,380				
Wyoming							2,000 lb sand-salt per 2-lane mile
PROVINCES							
Alberta	69/70	16,494	324				500 lb/2-lane mile NaCl max.
	70/71	26,910	240				
	71/72	23,461	50				
B.C.		45,000 (u)					100 to 300 lb/lane mile
H.S.	69/70	59,448				7.1	300 to 600 lb/2-lane mile; 70/71
	70/71	121,328				13.9	ave.: 490; 71/72 ave.: 450
	71/72	145,755				15.4	
Ontario	70/71	363,264					Sand: 2,000 lb/2-lane mile;
	71/72	419,137					salt: 450 lb/2-lane mile
	72/73	336,959					

(continued)

TABLE 2-7 (continued)

Agency	Year	NaCl (tons)	$CaCl_2$ (tons)	Sand (tons)	Other	Tons/lane mile	Application rates
		Annual totals					
TOLL ROADS							
Roads							
Illinois State Toll Highway Authority		44,000	691	7,740			500 to 600 lb/lane mile
New York Thruway	69/70	107,958				37.2	
	70/71	120,486				41.6	
	71/72	121,904				42.3	
Ohio Turnpike	69/70	26,645	1,335				400 lb/mile for snow; 200 lb/mile of 2:1 NaCl-$CaCl_2$ for freezing rain
	70/71	27,162	1,363		29,498		
	71/72	24,638	837				
COUNTY							
Hennepin (Minnesota)	70/71	11,252					250 lb/lane mile max.
	71/72	7,541					
	72/73	5,260					
CITIES							
Milwaukee	69/70	39,951					100 to 450 lb/lane mile
	70/71	43,257					
	71/72	38,940					
New York City	70/71	128,928					1 oz/yd^2 (salt only)
	71/72	129,946					
	72/73	30,300					
Seattle	69/70	27	19				600 lb/2-lane mile
	70/71	2,320	3				
	71/72	4,120	44				
Toronto	70/71	65,570					700 lb/lane mile
	71/72	66,141					
	72/73	38,000					

TABLE 2-8. STATE SNOW AND ICE CONTROL MATERIALS USE (SALT INSTITUTE, 1984)

			Winter 1981-1982				Winter 1982-1983			
			Calcium chloride				Calcium chloride			
State	Total lane miles	Pavement miles	Salt (tons)	Dry (tons)	Liquid (gal)	Abrasives (tons)	Salt (tons)	Dry (tons)	Liquid (gal)	Abrasives (tons)
Alaska	1,020	900	450	300	250,000	18,225[a]	355	250	200,000	18,225[a]
Arizona	16,650	0	394	44	0	56,714	413	25	0	56,000
Arkansas	34,852	0	2,510	576	0	16,597	856	246	0	9,155
California	53,000	12,900	13,600	25	0	200,000				
Colorado	32,000	32,000	22,460	0	0	351,519	10,896	0	0	434,837
Connecticut	10,160	0	103,201	600	0	380,641[a]	51,934	600	0	169,598[a]
Delaware	9,971	2,543	8,913	0	0	18,000	7,055	0	0	7,714
Florida										
Georgia	41,809	13,900	18,500	400	0	12,200	8,200	60	0	7,800
Idaho	11,512	0	11,000	0	0	228,000	11,000	0	0	192,000
Illinois	38,515		304,184	280	228,500		206,000	520	115,150	
Indiana	31,036	14,559	313,365	204	88,252	278,193	116,650	44	90	108,619
Iowa	24,300	0	64,000	2,260	24,000	145,000	60,400	2,225	9,500	116,000
Kansas	22,371	5,688	35,490	0	0		31,630	0	0	65,000

(continued)

TABLE 2-8 (continued)

State	Total lane miles	Pavement miles	Winter 1981-1982				Winter 1982-1983			
				Calcium chloride				Calcium chloride		
			Salt (tons)	Dry (tons)	Liquid (gal)	Abrasives (tons)	Salt (tons)	Dry (tons)	Liquid (gal)	Abrasives (tons)
Kentucky	53,846[b]	4,966[b]	73,275	550	0		32,964	107	0	
Louisiana	38,191	0	827	0	0	0	23	0	0	0
Maine	7,877	1,178	51,676	600		519,750	49,202	535		472,500[a]
Maryland	14,600	0	155,758	1,914		71,400	82,499	978		30,859
Massachusetts	12,000		262,000	3,600	0	184,000	178,500	2,842	0	95,000
Michigan	13,667	4,695	397,000	210	0	17,000	229,000	267	0	10,000
Minnesota	28,724	4,162	118,587	310	0	291,204	127,957	280	0	288,893
Mississippi	23,391	0	332				285			
Missouri	69,664		90,963	4,615	0		75,111	3,373	0	
Montana	18,790	18,790	2,817	16	0	160,000	3,245	28	0	200,000
Nebraska	22,000		22,221	464	34,642	84,877	24,899	556	25,974	86,734
Nevada	12,608	11,340	8,500	0	0	51,000	9,831	0	0	51,000
New Hampshire	8,630	8,406	138,692	293	0	210,135	93,813	228	0	151,322
New Jersey	10,366	10,366	54,500	980	273,000	12,400	35,700	580	228,000	4,200
New Mexico	27,450	20,000	16,000	0	0	64,000	23,000	0	0	80,000

(continued)

TABLE 2-8 (continued)

State	Total lane miles	Pavement miles	Winter 1981-1982				Winter 1982-1983			
				Calcium chloride				Calcium chloride		
			Salt (tons)	Dry (tons)	Liquid (gal)	Abrasives (tons)	Salt (tons)	Dry (tons)	Liquid (gal)	Abrasives (tons)
New York	29,780	29,780	443,000	800	0	899,000	300,000	300	0	460,000
North Carolina	112,573	23,342	45,264	192	0		36,573	160	0	
North Dakota	15,800		8,222	0	69,500[b]	35,000	8,719	217,800[b]	0	38,000
Ohio	42,192	0	401,285	1,175	224,014	239,087	184,341	195	113,291	128,976
Oklahoma	25,935	0	9,300	0		36,000	18,770	0		72,000
Oregon	17,895		0	0	449,016		456		424,988	
Pennsylvania	77,000		500,000	5,000	0	1,200,000	231,000	5,000	0	655,000
Rhode Island	3,015	3,015	56,280	88	0	86,094	29,297	132	0	45,000
South Carolina	84,450	3,450	1,988	388	0	10,000	897	286	0	4,750
South Dakota	18,216		4,345	7	0	52,920	3,697	5	0	45,002
Tennessee	25,087	25,087	51,000	740	0	51,000			0	
Utah	22,000		79,540	0	0	125,000	79,720	0	0	125,000
Vermont	6,079	6,079	71,904	0	0	154,648[a]	65,647	0	0	106,654[a]
Virginia	112,814	17,350	178,500	2,000	0	400,000	95,000	1,000	0	255,000
Washington	16,778	0	10,000	0	0	360,445	7,500	0	0	203,531

(continued)

TABLE 2-8 (continued)

State	Total lane miles	Pavement miles	Winter 1981-1982				Winter 1982-1983			
				Calcium chloride				Calcium chloride		
			Salt (tons)	Dry (tons)	Liquid (gal)	Abrasives (tons)	Salt (tons)	Dry (tons)	Liquid (gal)	Abrasives (tons)
West Virginia	70,000	21,000	90,636	1,009	0	239,655	52,709	314	0	178,642
Wisconsin	25,774	25,774	236,790	755	70,000	26,585	229,803	648	40,000	25,913
Wyoming	15,743	0	5,000	0	0	113,000	6,340	0	0	127,000

[a] Cubic yards of abrasives converted to tons on the basis of 1 yd^3 equals 2,700 lb—for calculation purposes only.

[b] Includes parkways.

TABLE 2-9. HIGHWAY SALT SALES BY U.S. MEMBERS OF THE SALT INSTITUTE (1989)

Year of record	Quantity sold (10^3 tons)[a]
7/77-6/78	10,900
7/78-6/79	11,300
7/79-6/80	8,110
7/80-6/81	7,240
7/81-6/82	9,790
7/82-6/83	7,270
7/83-6/84	10,300
7/84-6/85	10,700
7/85-6/86	11,100
7/86-6/87	9,460
7/87-6/88	11,100
7/88-6/89	10,200

[a] Rounded to three significant figures.

TABLE 2-10. STORMFIGHTING GUIDELINES OF THE SALT INSTITUTE

Environmental condition	Recommended application
CONDITION 1: **Temperature** Near 30 **Precipitation** Snow, sleet, or freezing rain **Road Surface** Wet	If snow or sleet, apply salt at 500 lb per two-lane mile. If snow or sleet continues and accumulates, plow and salt simultaneously. If freezing rain, apply salt at 200 lb per two-lane mile. If rain continues to freeze, reapply salt at 200 lb per two-lane mile.
CONDITION 2: **Temperature** Below 30 or falling **Precipitation** Snow, sleet, or freezing rain **Road Surface** Wet or sticky	Apply salt at 300 to 800 lb per two-lane mile, depending on accumulation rate. As snowfall continues and accumulates, plow and repeat salt application. If freezing rain, apply salt at 200 to 400 lb per two-lane mile.
CONDITION 3: **Temperature** Below 20 and falling **Precipitation** Dry snow **Road Surface** Dry	Plow as soon as possible. Do not apply salt. Continue to plow and patrol to check for wet, packed, or icy spots; treat them with heavy salt applications.
CONDITION 4: **Temperature** Below 20 **Precipitation** Snow, sleet, or freezing rain **Road Surface** Wet	Apply salt at 600 to 800 lb per two-lane mile, as required. If snow or sleet continues and accumulates, plow and salt simultaneously. If temperature starts to rise, apply salt at 500 to 600 lb per two-lane mile, wait for salt to react before plowing. Continue until safe pavement is obtained.
CONDITION 5: **Temperature** Below 10 **Precipitation** Snow or freezing rain **Road Surface** Accumulation of packed snow or ice	Apply salt at rate of 800 lb per two-lane mile or salt-treated abrasives at rate of 1,500 to 2,000 lb per two-lane mile. When snow or ice becomes mealy or slushy, plow. Repeat application and plowing as necessary.

NOTE: The light, 200-lb application called for in Conditions 1 and 2 must be repeated often for the duration of the condition.

TABLE 2-11. GUIDELINES FOR CHEMICAL APPLICATION RATES (AASHTO, 1976)

Weather conditions			Application rate (pounds of material per mile of two-lane road or two lanes of divided)			
Temperature	Pavement conditions	Precipitation	Low- and high-speed multilane divided	Two- and three-lane primary	Two-lane secondary	Instructions
30°F and above	Wet	Snow	300 salt	300 salt	300 salt	• Wait at least 0.5 h before plowing
		Sleet or freezing rain	200 salt	200 salt	200 salt	• Reapply as necessary
25°-30°F	Wet	Snow or sleet	Initial at 400 salt; repeat at 200 salt	Initial at 400 salt; repeat at 200 salt	Initial at 400 salt; repeat at 200 salt	• Wait at least 0.5 h before plowing; repeat
		Freezing rain	Initial at 300 salt; repeat at 200 salt	Initial at 300 salt; repeat at 200 salt	Initial at 300 salt; repeat at 200 salt	• Repeat as necessary
20°-25°F	Wet	Snow or sleet	Initial at 500 salt; repeat at 250 salt	Initial at 500 salt; repeat at 250 salt	1,200 of 5:1 sand/ salt; repeat same	• Wait about 0.75 h before plowing; repeat
		Freezing rain	Initial at 400 salt; repeat at 300 salt	Initial at 400 salt; repeat at 300 salt		• Repeat as necessary
15°-20°F	Dry	Dry snow	Plow	Plow	Plow	• Treat hazardous areas with 1,200 of 20:1 sand/salt
	Wet	Wet snow or sleet	500 of 3:1 salt/ calcium chloride	500 of 3:1 salt/ calcium chloride	1,200 of 5:1 sand	• Wait about 1 h before plowing; continue plowing until storm ends; then repeat application
Below 15°F	Dry	Dry snow	Plow	Plow	Plow	• Treat hazardous area with 1,200 of 20:1 sand/salt

use abrasives mixed with lower proportions of salt, and use alternatives to chloride salts. However, highway maintenance personnel know that if they do not apply sufficient salt in time, a compacted snow mass builds up that may take 3 to 5 days to remove by "laborious, costly, time-consuming, and marginally ineffective methods." Consequently, minimizing deicing chemical use is often considered not a good idea for safety and cost reasons.

Tailgate sanding trucks commonly spread antiskid materials. The most popular truck is reported as a five-ton, two-axle, heavy-duty truck. These rear-dump trucks can have spinning disks or a roller extending the width of the truck tailgate that cast the sand/salt out over two lanes of traffic, or may simply discharge the mixture straight down upon the narrow traffic path being travelled, often only 1 to 3 ft wide. Often snowplowing and salting/sanding operations are done with the same truck during the same pass. However, front-dump spreaders are used in Maine so that the truck itself has traction on the newly sanded/salted surface.

2.3 REMOVAL TECHNIQUES

Dust generation potential can be reduced if the fine materials left on roadways after pavement drying are cleaned up promptly and without further spreading and resuspension. Prompt cleaning also keeps abrasives from being ground into small particles by road traffic or freeze/thawing. Quick cleanup may not be mandated, however, if a new snowstorm is likely.

Helmers (1986) and Oeberg (1985) attached glass plates to the rear bumpers of cars to collect samples of antiskid materials. After exposure of the glass plates while driving on wet roadways, light transmission through the plates was measured to give a semiquantitative estimate of the comparative "dirtiness" of the roads. These studies reported that salted roads were "dirtier" than sanded ones as determined by light transmission through the collection plates.

Many agencies contacted by phone stated that they clean up abrasives applied to roadways, mostly during the spring, following the end of the snow season. Montana cleans only urban roads with vacuum sweepers. Cleanup operations begin in late February to keep strong spring winds from picking up the remaining sand on roadways causing a sandblasting action. Wyoming representatives, however, responded that they clean roadways whenever the weather permits if there is a heavy buildup of sand. In rural areas of Wyoming, sand is swept to the side of the road, while in urban areas, sand is picked up by street cleaners. In season, Colorado cleans their highways at night (in the Denver maintenance area) using broom sweepers. Missouri "routinely" cleans up their highways.

One major reason for cleanup operations in cities is to prevent abrasives from being deposited into catch basins or sewers. Catch basins are emptied at considerable expense. Abrasives may plug combination storm/sanitary sewer systems if there are no

catch basins and streets are not cleaned. Cleanup operations in Maine and Minneapolis also include the washing of bridges with pressure hoses.

SECTION 3

MEASUREMENT METHODS FOR PHYSICAL PROPERTIES

As stated in Section 1, the amount of PM_{10} generated from paved roadways is directly related to the silt loading of the surface material available for reentrainment by passing vehicles. Abrasives and deicing chemicals add temporary, but substantial, amounts of silt-size particles to the road which, if not removed, will increase PM_{10} emissions and their associated air quality impact. These fine particles are either applied directly to the road surface with the abrasive or chemical during initial treatment or are created through attrition, dissolution, etc., while on the road surface.

The potential of a particular material to provide additional silt loading on a road surface (and thus PM_{10}) is directly related to its physical (or chemical) properties. In this section, various methods for measuring the properties of antiskid materials are presented. These methods can be divided into three general categories which include: silt measurement methods; durability measurement methods; and measurement of other applicable properties. Although this discussion will be directed mainly to abrasives, some discussion of deicing chemicals will also be provided in Section 3.4.

Finally, a number of the standard methods found in the literature are not directly applicable to some types of antiskid materials. For this reason, modifications to the standard techniques were required in certain cases. These modified methods are discussed in Section 3.5.

3.1 SILT MEASUREMENT METHODS

In general, there are two basic techniques for measuring the silt content (% less than 200 mesh or 75 μm) of a material: mechanical classification and instrumental methods. Each will be discussed as related to current practice.

3.1.1 Mechanical Classification Methods

The most widely used technique for determination of silt content is through a combination of wet and dry sieving according to American Society of Testing and Materials (ASTM) Methods C 136 and C 117 (ASTM, 1984a and 1987). These methods correspond to American Association of State Highway and Transportation Officials (AASHTO) Methods T-27 and T-11, respectively (AASHTO, 1984; AASHTO, 1985a). Copies of the ASTM methods are included in Appendix D.

In the standard ASTM and AASHTO methods, an aggregate sample is first washed through a 200 mesh sieve to determine the amount of material less than 75 μM in physical diameter. The remaining sample is then dry-sieved to determine the gradation of particles in the larger size ranges as well as any residual material passing the 200 mesh screen. The weight of the < 200 mesh material determined by washing is added to that collected during dry sieving to determine the total silt content of the original sample. (Note that the method used by MRI in the development of the PM_{10} emission factor equation uses only dry sieving to determine silt content.) The approximate 1989 cost of the two ASTM analyses at a local laboratory in Kansas City is $35.

The above technique is used by most transportation agencies for determining the gradation of aggregate materials, including those used for skid control. Size gradation specifications are normally developed for aggregates used in Portland cement concrete mixes for road paving which rely heavily on the ASTM or AASHTO methods.

3.1.2 Instrumental Methods for Silt Determination

Although not as commonly used, various instrumental methods are available for the determination of the silt content of finely divided particulate matter. In general these methods include: microscopy, sensing zone instruments, elutriation and centrifugal classification, mercury intrusion, gravity sedimentation, centrifugal sedimentation, hydrodynamic chromatography, and mercury porosimetry. Table 3-1 provides a further classification of instruments falling into each of the above categories as well as examples of commercially available equipment.

Although specifications vary from device to device, the above instruments are limited to measurement of particles < ~ 200 μm in diameter. These instruments can, however, offer the advantage of automatic operation (thus reducing analytical error) as well as providing data on particle size distribution, surface area, etc., which may be useful in material selection. In general, instrumental analysis methods are relatively expensive and thus are not widely used by transportation agencies.

3.2 DURABILITY MEASUREMENT METHODS

In general, there are four basic methods which can be used for determining the durability of an aggregate material. These include abrasion and impact tests; wet aggregate durability tests; freeze-thaw tests; and petrographic methods. Although these tests were originally developed to measure the durability of aggregates used in concrete mixes for road paving, they are also useful in the evaluation of skid control abrasives (see Section 5). The following describes the various methods included in the above categories.

TABLE 3-1. SUMMARY OF INSTRUMENTAL METHODS OF PARTICLE SIZE ANALYSIS

- Microscopic methods:

  Optical microscopy
  Electron microscopy (TEM and SEM)
  Automated image analysis (e.g., LaMont Analyzer)

- Sensing zone methods:

  Electrical resistance (e.g., Coulter Counter)
  Optical (including laser)
  Photoextinction (e.g., HIAC PA 720)
  Forward and right-angle scattering (e.g., L&N Microtrac)
  Acoustic

- Elutriation and centrifugal classification methods:

  Laminar flow (e.g., Roller analyzer)
  Cyclone-elutriators (e.g., Cyclosizer)
  Centrifugal classifiers (e.g., Bahco Micro-Particle Classifier)

- Gravity sedimentation methods:

  Turbidimetry (e.g., Wagner Turbidimeter)
  Sedimentation balances (e.g., Micromerograph)
  X-ray (e.g., SediGraph 5000D)
  Photoextinction (e.g., SediGraph-L)

- Centrifugal sedimentation methods:

  Mass accumulation (e.g., MSA)
  Photoextinction (e.g., Joyce-Loebl Disc Centrifuge)
  X-ray

- Hydrodynamic chromatography

- Mercury porosimetry

3.2.1 Abrasion and Impact Tests

One measure of aggregate durability is its ability to withstand abrasion and impact in service. There are three methods which fall into the category of abrasion/impact tests. These are the Los Angeles abrasion test, the aggregate impact test, and the aggregate crushing test. Each is described below.

The Los Angeles Abrasion Test is outlined in ASTM Method C 131 and AASHTO Method T-96 for small-size coarse aggregate (ASTM, 1989; AASHTO, 1983). The Los Angeles test is intended to measure the degradation of washed mineral aggregates of specific particle size (e.g., 4.75 to 2.36 mm) due to a combination of abrasion (or attrition), impact, and grinding in a rotating ball mill. Each graded material sample is sieved after milling to determine the amount of fines generated by the process. The number of balls used in the mill depends on the original gradation of the test sample analyzed.

A copy of the Los Angeles abrasion test has been included in Appendix E. The approximate 1989 cost of a standard ASTM Method 131 or AASHTO Method T-96 analysis is $50 at a local laboratory in Kansas City.

The Aggregate Impact Test is given in British Standard 812 and also used in the United States for research purposes (Woodside and Peden, 1983; Hegmon and Meyer, 1968). In this test, a small aggregate sample is placed in an instrument where a standard weight is repeatedly dropped onto the material thus attenuating the sample. Degradation is determined by differences in gradation before and after impact (Hegmon and Meyer, 1968).

The Aggregate Crushing Test is also given in British Standard 812 (Woodside and Peden, 1983). In this test, an aggregate sample is crushed at a constant rate so that the compressive force at the end of the 10-min test period is 40 tonnes (44 tons). The method gives rise to the formation of a cushioning layer formed from the matrix composed of weaker crushed material, which effectively dampens the effect of loading on the enclosed sample. Both the aggregate crushing test and aggregate impact test are used extensively in Europe to determine the durability of aggregate used in road pavement (Woodside and Peden, 1983; Anon, 1979).

The values obtained from the above tests were correlated with one another by Woodside and Peden (1983) using experimental data for 13 different aggregate materials used in paving mixes. The correlation of the aggregate crushing value (ACV) with the Los Angeles abrasion value (LAAV) is given by the following equation (Woodside and Peden, 1983):

$$ACV = 0.8013\ LAAV + 3.5853 \qquad (3\text{-}1)$$

The correlation coefficient for the above relationship is 0.9042.

Using the same data set, the correlation of aggregate impact value (AIV) with the Los Angeles abrasion value (LAAV) was determined by MRI to be:

$$AIV = 0.6535\ LAAV + 3.1778 \qquad (3\text{-}2)$$

The correlation coefficient for the above relationship is 0.9723. As shown by Equations (3-1) and (3-2), the results of the three abrasion/impact tests are intercorrelated with one another. This intercorrelation will be discussed in more detail later in this report.

3.2.2 Wet Aggregate Durability Tests

All wet aggregate durability tests are based on the basic techniques outlined in AASHTO Method T-210 and ASTM Method D 3744 for fine aggregate material (AASHTO, 1964; ASTM, 1985c). Variations of these methods have been developed by Maine, Washington (Method 113A), Oregon, and Alaska (Method T-13). The purpose of this method is to determine the durability of an aggregate material based on its relative resistance to the production of detrimental, claylike fines when subjected to mechanical agitation in water.

In the basic method, a dry graded sample is placed in a closed vessel along with 1000 mL of distilled (or deionized) water and agitated on a sieve shaker for 2 min. After agitation, the degraded material is washed through a 200 mesh screen and the material > 200 mesh is dried and dry-sieved to obtain the size distribution. After sieving, the individual separates are recombined, a calcium chloride solution added to a subsample of the material, and the material reshaken and allowed to settle. The "clay" layer and "sand" layer is then measured with the "durability index" calculated from the values obtained.

A number of variations to the above method have been developed by state transportation agencies. These variations include changes in both methodology or in the calculation procedure. Copies of the various state-generated wet durability test methods are included in Appendix F.

The specification of a minimum durability value for paving aggregates using the above tests will vary from state to state. For example, Washington specifies a minimum degradation value of 50 (using its particular test method) as compared to Maine which specifies a minimum value of 40 (using its method) (Norburg, 1981). It would be expected that these specifications may also be used as general guidelines for the selection of antiskid abrasives as well.

3.2.3 Freeze-Thaw Tests

Another measure of aggregate durability is its susceptibility to fracture during freeze-thaw cycles. This is referred to as "soundness" and is determined using the sodium/magnesium sulfate test specified in ASTM C 88 and AASHTO T-104 (ASTM, 1983;

AASHTO, 1985b). The 1989 cost of analysis for either the ASTM or AASHTO methods is approximately $65 at a local laboratory in Kansas City.

The above methods estimate the soundness of individual aggregate size separates by repeated immersion in a saturated salt solution followed by oven drying to partially (or completely) dehydrate the salt precipitate in the permeable pore spaces. The internal expansive force, derived from the rehydration of the salt upon reimmersion, simulates the expansion of water on freezing. After the final immersion/drying cycle, degradation is determined by sieving the sample over the same sieve on which it was retained before the test to determine the percent loss. Since most abrasives used for skid control are mixed with salt either before or after application, this test may be of particular interest in determining the durability of such materials in service.

3.2.4 Petrographic Methods

The final durability measurement techniques to be discussed are pètrographic methods which evaluate the mineral composition of fine aggregate materials. The nomenclature used to describe the constituents of mineral aggregates is provided in ASTM Method C 294 with the petrographic examination of this material described in ASTM Method C-295 (ASTM, 1969; ASTM 1985a). The approximate cost of analysis for ASTM C-295 is $2,000 for a laboratory located in Chicago.

The above ASTM methods are only intended to determine the mineral content of a particular material and thus do not attempt to relate mineralogy to durability. However, the Petrographic Number Method has been developed in Canada for such a determination (Hudec, 1984). This method is basically a subjective method of classifying crushed rock particles into four discrete categories of good, fair, poor, and bad (deleterious) aggregate (1 = good; 3 = fair; 6 = poor; 10 = bad).

Hudec (1984) related the petrographic number (PN) determined by the above method to various other measured parameters by step-wise multiple linear regression. The results of this analysis obtained the following relationship:

$$PN = 4.406 + 0.144\ Ab + 1.805\ Ad - 0.165\ Gr - (2.014\ Ad/VAd) - 1.004\ Hd \qquad (3\text{-}3)$$

where:

PN = petrographic number (dimensionless)

Ab = low intensity abrasion value for < 6.7 mm material (dimensionless)

Ad = adsorbed water (%)

Gr = grain size (mm)

VAd = vacuum water adsorption (%), by boiling method

Hd = hardness

As shown by the above relationship, the durability (as determined by petrography) of an aggregate decreases with its susceptibility to abrasion and water absorption and increases with grain size and hardness of the particles.

3.3 ANALYSIS METHODS FOR OTHER PROPERTIES

In addition to the above, there is a wide variety of other properties related to the durability and fines-generating potential of abrasives used in ice and snow control. These are too numerous to describe in detail here. However, Table 3-2 provides a summary of the various methods and the basis for their applicability to skid control abrasives. Analysis cost estimates are also provided in Table 3-2 based on a laboratory located in either Kansas City or Chicago.

Like those described above, most of the methods described in Table 3-2 are related to the selection of aggregates for use in portland cement concrete mixtures. A standard specification for concrete aggregates is published in ASTM Method C 33 which can be used as a general guide for material selection (ASTM, 1985b). Please note, however, that some transportation agencies use rejected concrete aggregate (e.g., sand) as a skid control abrasive.

3.4 MEASUREMENT METHODS FOR DEICING CHEMICALS

Rock salt used for road deicing purposes is composed mostly of NaCl which is believed not to remain on the road surface in any substantial amount after the storm. The NaCl is either washed away with the storm runoff, entrained by passed vehicles, or retained by the pavement itself. However, rock salt contains appreciable quantities (up to 6% for Kansas salt) of water-insoluble mineral matter which can remain on the road surface for extended periods (Kaufmann, 1968). This insoluble mineral matter consists of very fine particles of $CaS0_4$, silica, alumina, ferric oxide, and dolomite. Therefore, in addition to gradation (see Section 3.1 above), the percent insoluble matter in rock salt is important in the generation of surface silt loading and thus PM_{10}.

To determine the percent insoluble material in rock salt using ASTM E 534, 25 g of sample is placed in 600 mL of heated water and stirred for a period of 60 min (ASTM, 1986). After stirring, the mixture is wet filtered to obtain the percent insoluble matter by gravimetric analysis. General specifications for sodium chloride are provided in ASTM Method D 632 (ASTM, 1984b).

TABLE 3-2. SUMMARY OF TEST METHODS RELATED TO ANTISKID MATERIALS

Method designation	Title of test method	Summary of test method	Significance of test to antiskid materials	Approximate cost of analysis[a]	Reference No.[b]
ASTM C 29 (AASHTO-T-19)	Unit Weight and Voids in Aggregate	A standard metal cup is sequentially filled with aggregate and repeatedly tamped with a rod. The weight of the aggregate in the cup is then measured with the percent voids calculated based on the dry bulk density of the aggregate and the equivalent weight of water occupying the cup volume.	The void fraction of an aggregate is related to the angularity of the particles. Highly angular particles are desired for good skid control.	$50	1, 2
ASTM C 128	Specific Gravity and Absorption of Fine Aggregate	The aggregate to be tested is immersed in water for a period of 24 h after which time it is partially air-dried such that it no longer holds a cylindrical shape. A 500-g sample of this material is then introduced into a pycnometer and filled with water. The pycnometer is weighed both with the aggregate sample/water mixture and with an equivalent volume of water. The sample is removed from the pycnometer, oven-dried, and the total moisture determined by gravimetric analysis. The bulk specific gravity and water absorption is then calculated from the test results.	Bulk specific gravity is needed for Method C 29 above. In addition, since application of abrasives is normally metered according to volume, bulk specific gravity can be used to determine the application rate on a weight basis. Finally, water absorption is related to soundness of an aggregate to withstand freeze-thaw cycles.	$25	1
ASTM C 142	Clay Lumps and Friable Particles in Aggregates	A dry-sieved (Method C 117) aggregate sample (> 1.18 mm) is immersed in water for a period of 24 h, after which the lumps and friable particles are individually broken by hand. The material is then wet-sieved and dried to determine the percent of the original sample consisting of lumps or friable particles.	Clay lumps and friable particles contained in skid control abrasives have a greater potential for the generation of fines when applied to a road surface.	$25	1
ASTM C 289	Potential Reactivity of Aggregates (Chemical Method)	A small aggregate sample containing particles ranging from 150 to 300 μm is immersed in a heated (80°C), 1.0 N solution of NaOH for a period of 24 h. At the end of this period, the solution containing dissolved SiO_2 is filtered from the aggregate, digested with concentrated HCl, and the solid SiO_2 repeatedly filtered from the reacted solution. The percent SiO_2 is calculated from the results of gravimetric analysis.	The silica (SiO_2) content of a fine aggregate used for skid control has been determined to be one of the most important factors in durability with high silica particles being most durable.	$150	1
ASTM C 672	Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals	In this method, concrete specimens are exposed to a 4% solution of CaCl (or other deicers) and repeatedly frozen and thawed for 16 to 18 h. The scaling of the specimen is determined visually over the desired number of cycles and a rating assigned from 0-5 (0 = no scaling) every 5 cycles (or every 25 cycles after 25 cycles have been made).	The ability of a road pavement to withstand the application of deicing chemicals is related to pavement breakup (i.e., scaling) and thus the production of additional fine particles for suspension. This test is not directly related to aggregate durability, however.	$600 (50 cycles)	1

(continued)

TABLE 3-2 (continued)

Method designation	Title of test method	Summary of test method	Significance of test to antiskid materials	Approximate cost of analysis[a]	Reference No.[b]
ASTM D 75 (AASHTO T-2)	Sampling of Aggregates	Grab sampling procedures are outlined for static and dynamic conditions.	Collection of a representative sample of antiskid materials.	Variable	1, 2
ASTM D 3398	Index of Aggregate Particle Shape and Texture	A sample of aggregate is placed in a cylindrical mold of known volume and repeatedly tamped with a rod of standard weight. The weight of material is determined after 10 and 50 drops of the rod to calculate the particle index.	Particle shape (high degree of angularity) and texture (coarse) are important in skid resistance. This method is an indirect measure of these two properties.	$560 (7 fractions)	1
ASTM E 660	Accelerated Polishing of Aggregates or Pavement Surfaces Using a Small-Wheel, Circular Track Polishing Machine	Pavement (bituminous or concrete) specimens are mounted on a track, over which four smooth, pneumatic tires are continuously run. A polishing curve is obtained over a period of ~ 8 h or until friction measurements show no substantial decrease with continued polishing. (Note that although pavement specimens are normally used, an immobilized aggregate sample could also be evaluated by the above method.)	The resistance of a skid control material to wear and polishing by the action of rotating tires is the most direct measure of durability currently available.	Unknown	1
AASHTO T-248 (ASTM C 702)	Reducing Field Samples of Aggregate to Testing Size	Sample splitting using a riffle and coning and quartering are described.	Collection of a representative sample of antiskid material for further analysis.	Variable	1, 2
None	Moh Hardness	Surface scratch hardness relative to empirical scale.	Material hardness is directly related to durability as measured by other methods.	$50	—

[a] Based on 1989 prices of an independent materials testing laboratory located in either Kansas City or Chicago.

[b] Reference 1 = *1990 Annual Book of ASTM Standards*, American Society of Testing and Materials, Philadelphia, Pennsylvania, 1990.
Reference 2 = *Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part II, Methods of Sampling and Testing*, 14th Edition, American Association of State Highway and Transportation Officials, Washington, D.C., August 1986.

3.5 MODIFICATIONS TO STANDARD TEST METHODS

Several of the ASTM methods described above cannot be used to analyze some types of antiskid materials as currently written. Therefore, MRI modified certain methods. In all cases, the original test method was preserved to the greatest extent practical with changes made only as required.

The following sections describe ASTM methods modified by MRI. These methods are:. Los Angeles abrasion loss; silt content; Vickers hardness; and insoluble matter in calcium magnesium acetate. Copies of the standard ASTM methods for these parameters are included in Appendices D, E, G, and H.

It can be safely assumed that ASTM methods are generally developed with sufficient data to validate the technique and determine its accuracy. Such is not the case, however, for methods modified in the current program. For these methods, accuracy could generally not be determined either from existing data or from data generated in the study. Instead, multiple analyses of commonly available materials were performed to partially assess the reproducibility (i.e., precision) of each modified method. This is discussed in more detail in Section 5.2.

3.5.1 Los Angeles Abrasion Loss

At present, the Los Angeles (LA) Abrasion test (ASTM C 131) is only applicable to aggregate larger than 2.36 mm (0.093 in). Since many abrasives used for ice and snow control are finer than 2.36 mm, minor modifications to ASTM C 131 are required. In addition, since silt size particles are of most concern in the assessment of PM_{10} emissions, the increase in the silt content after exposure in the LA test machine was selected as an indicator of durability. The modifications made to ASTM C 131 are shown in Table 3-3.

Upon examination of the test data produced by the procedure outlined in Table 3-3 (see Section 5.2), it was decided that further revisions to the method were necessary. Therefore, the methodology shown in Table 3-3 was altered slightly to that shown in Table 3-4. The method shown in Table 3-4 provides slightly more detail and a revised calculation scheme which more closely reflects the intent of the standard technique. Table 3-4 was used for analysis of all antiskid abrasives in the remainder of the program.

It should be noted, however, that further modification to Table 3-4 might be recommended in future efforts based on the experience gained during Phase 2. For example, all materials should be normalized to 0% initial silt content by washing prior to analysis. This technique is used in the original LA abrasion method and would improve statistical analysis of the test data.

TABLE 3-3. MODIFICATIONS TO ASTM METHOD C 131-89

The standard ASTM methodology should be used with the following modifications:

5. Apparatus

5.4.1 The weight of the test sample placed in the Testing Machine shall be 5,000 ± 10 g along with a charge of six (6) standard spheres.

8. Procedure

8.1 Split the sample into two equal fractions according to Method C 702. Sieve the first fraction according to the procedure outlined in Table A and record the results. Weigh the charge of spheres to be introduced into the testing machine and record the results.

8.2 Place the second sample fraction and the charge in the Los Angeles testing machine and rotate the machine at a speed of 30 to 33 rpm for 500 revolutions. After the prescribed number of revolutions, discharge the material from the machine and sieve the sample material using the procedure shown in Table A. Record the results.

TABLE A. SAMPLE SIEVING PROCEDURE

1. Select the appropriate 8-in diameter, 2-in deep sieve sizes. Recommended U.S. Standard Series sizes are 3/8 in, No. 4, No. 20, No. 40, No. 100, No. 140, No. 200, and a pan. Comparable Tyler Series sizes can also be utilized. The No. 20 and the No. 200 are mandatory. The others can be varied if the recommended sieves are not available or if buildup on one particular sieve during sieving indicates that an intermediate sieve should be inserted.
2. Obtain a mechanical sieving device such as vibratory shaker or a Roto-Tap.
3. Clean the sieves with compressed air and/or a soft brush. Material lodged in the sieve openings or adhering to the sides of the sieve should be removed (if possible) without handling the screen roughly.
4. Obtain a scale (capacity of at least 1,600 g) and record make, capacity, smallest division, date of last calibration, and accuracy (if available).
5. Tare sieves and pan. Check the zero before every weighing. Record weights.
6. After nesting the sieves in decreasing order with pan at the bottom, dump dried laboratory sample (probably immediately after moisture analysis) into the top sieve. Brush fine material adhering to the sides of the container into the top sieve and cover the top sieve with a special lid normally purchased with the pan.
7. Place nested sieves into the mechanical device and sieve for 20 min. Remove the pan containing the minus No. 200 fraction and weigh. Replace pan beneath the sieves and sieve for another 10 min. Remove pan and weigh. When the differences between two successive pan sample weighings (where the tare of the pan has been subtracted) is less than 3.0%, the sieving is complete.
8. Weigh each sieve and its contents and record the weight. Check the zero before every weighing.
9. Collect the laboratory sample and place the sample in a separate container if further analysis is expected.

TABLE 3-4. MODIFICATIONS TO ASTM METHOD C 131-89 FOR AGGREGATE MATERIAL < 2.36 MM

The standard ASTM methodology should be used with the following modifications:

5. Apparatus

5.4.1 The weight of the test sample placed in the Testing Machine shall be 5,000 ± 10 g along with a charge of six (6) standard spheres.

8. Procedure

8.1 Split the sample into two equal fractions according to Method C 702. Sieve the first fraction according to the procedure outlined in Table A and record the results. Weigh the charge of spheres to be introduced into the testing machine and record the results.

8.2 Place the second sample fraction (as received) and the charge in the Los Angeles testing machine and rotate the machine at a speed of 30 to 33 rpm for 500 revolutions. After the prescribed number of revolutions, discharge the material from the machine, separate the charge, and sieve the sample material using the procedure shown in Table A. Record the results.

TABLE A. SAMPLE SIEVING PROCEDURE

1. Select the appropriate 8-in diameter, 2-in deep sieve sizes. Recommended U.S. Standard Series sizes are 3/8 in, No. 4, No. 20, No. 40, No. 100, No. 140, No. 200, and a pan. Comparable Tyler Series sizes can also be utilized. The No. 20 and the No. 200 are mandatory. The others can be varied if the recommended sieves are not available or if buildup on one particular sieve during sieving indicates that an intermediate sieve should be inserted.
2. Obtain a mechanical sieving device such as vibratory shaker or a Roto-Tap.
3. Clean the sieves with compressed air and/or a soft brush. Material lodged in the sieve openings or adhering to the sides of the sieve should be removed (if possible) without handling the screen roughly.
4. Obtain a scale (capacity of at least 1,600 g) and record make, capacity, smallest division, date of last calibration, and accuracy (if available).
5. Tare sieves and pan. Check the zero before every weighing. Record weights.
6. After nesting the sieves in decreasing order with pan at the bottom, dump dried laboratory sample (probably immediately after moisture analysis) into the top sieve. Brush fine material adhering to the sides of the container into the top sieve and cover the top sieve with a special lid normally purchased with the pan.
7. Place nested sieves into the mechanical device and sieve for 20 min. Remove the pan containing the minus No. 200 fraction and weigh. Replace pan beneath the sieves and sieve for another 10 min. Remove pan and weigh. When the differences between two successive pan sample weighings (where the tare of the pan has been subtracted) is less than 3.0%, the sieving is complete.
8. Weigh each sieve and its contents and record the weight. Check the zero before every weighing.
9. Collect the laboratory sample and place the sample in a separate container if further analysis is expected.

TABLE 3-4 (continued)

9. Calculation

9.1 Determine the abrasion loss as a percentage using the following equation:

$$aL = \frac{S_i - S_f}{S_i} \times 100$$

where:

aL	=	LA abrasion loss (weight percent)
S_i	=	Weight percent of material > 200 mesh (75 μm) in original sample
S_f	=	Weight percent of material > 200 mesh (75 μm) in sample after exposure in Los Angeles Testing Machine

The calculation scheme shown in Table 3-4 would also be revised to the following form:

$$aL = \frac{W_s}{W_t} \times 100 \qquad (3\text{-}4)$$

Where:
- aL = LA abrasion loss (weight %)
- W_s = Weight of sample less than 200 mesh (75 μmP) after exposure in Test Machine (g).
- W_t = Total weight of original sample (g)

3.5.2 Silt Content

Since 1973, MRI has used a modified version of ASTM C 136 for determination of silt content based entirely on dry sieving. (ASTM C-136 requires that the silt sized particles be wet sieved using ASTM C 117.) Dry sieving was originally selected by MRI since it was believed to more adequately reflect natural processes (e.g., agglomeration) occurring on the surface of paved roadways. The MRI protocol has been used extensively in the development of the AP-42 emission factor equations (USEPA, 1985). This method is, therefore, recommended for the analysis of the silt content for both abrasives and deicers in lieu of ASTM C-136 and 117, respectively. The silt analysis procedure developed by MRI is shown in Table 3-5.

3.5.3 Vickers Hardness

The determination of Vickers Hardness (ASTM E 384) involves the optical measurement of impressions made in the test specimen using a diamond indenter (ASTM, 1989). Because the method was originally developed for the analysis of metals, modifications were required for application to fine aggregate materials. These modifications are shown in Table 3-6.

The modifications in Table 3-6 are based on techniques developed by Dr. Richard Hagni at the University of Missouri-Rolla for the analysis of geologic materials. The method involves the immobilization of abrasive particles in an epoxy mold which is then polished prior to analysis. Four representative particles are analyzed from those contained in the polished section and an average hardness number obtained for the entire specimen. The technique was used with good success as shown in Section 5 of this report.

TABLE 3-5. SILT ANALYSIS PROCEDURES

1. Select the appropriate 8-in diameter, 2-in deep sieve sizes. Recommended U.S. Standard Series sizes are 3/8 in, No. 4, No. 20, No. 40, No. 100, No. 140, No. 200, and a pan. Comparable Tyler Series sizes can also be utilized. The No. 20 and the No. 200 are mandatory. The others can be varied if the recommended sieves are not available or if buildup on one particular sieve during sieving indicates that an intermediate sieve should be inserted.

2. Obtain a mechanical sieving device such as vibratory shaker or a Roto-Tap.

3. Clean the sieves with compressed air and/or a soft brush. Material lodged in the sieve openings or adhering to the sides of the sieve should be removed (if possible) without handling the screen roughly.

4. Obtain a scale (capacity of at least 1,600 g) and record make, capacity, smallest division, date of last calibration, and accuracy (if available).

5. Tare sieves and pan. Check the zero before every weighing. Record weights.

6. After nesting the sieves in decreasing order with pan at the bottom, dump dried laboratory sample (probably immediately after moisture analysis) into the top sieve. Brush fine material adhering to the sides of the container into the top sieve and cover the top sieve with a special lid normally purchased with the pan.

7. Place nested sieves into the mechanical device and sieve for 20 min. Remove the pan containing the minus No. 200 fraction and weigh. Replace pan beneath the sieves and sieve for another 10 min. Remove pan and weigh. When the differences between two successive pan sample weighings (where the tare of the pan has been subtracted) is less than 3.0%, the sieving is complete.

8. Weigh each sieve and its contents and record the weight. Check the zero before every weighing.

9. Collect the laboratory sample and place the sample in a separate container if further analysis is expected.

TABLE 3-6. MODIFICATIONS TO ASTM E 384-89 TO INCORPORATE FINE AGGREGATE MATERIALS

The standard ASTM methodology should be used with the following modifications:

7. Test Specimens

7.1 Mount each aggregate sample in an appropriate epoxy resin mold. Grind and polish the surface of the mold according to standard techniques.

8. Procedure

8.1 Select at least four (4) particles from each mold for analysis. The particles should be representative of the bulk material present in the specimen. Variations in reflectance, polishing hardness, color, and anisotropism should be noted and particles excluded which do not represent the bulk of the material present. For materials of greatly varied lithologic character, particles with different lithology should be selected which represent the entire sample.

8.2 Delete

8.4.7 Measure a total of five (5) indentations on each of the four particles selected for analysis to obtain a total of 20 indentations for each polished section. Read the two diagonals of the indentation to within 0.25 µm or 0.4%, whichever is larger, and determine the average of the diagonal lengths. For materials with very low reflectance values (e.g., calcite, quartz, etc.), indentation measurements should be performed using an appropriate microscope equipped with dark field illumination or other special types of lighting arrangements.

8.4.8 Indentations which exhibit obvious problems shall not be measured. (For example, an indentation that shows cracks at its edge.) Instead, repeat the indentation elsewhere on the same particle or select another representative particle from the same polished section.

8.5.2 Compute the mean HV for the polished section by calculating the Vickers hardness number for each of the 20 indentations from the equation given in Section 4.3.1.1 or from the information given in Table 2. Average the 20 measurements to obtain the mean for the sample. To obtain the hardness number from the table, read the HV (1 g_f) corresponding to the average of the two measured diagonal lengths (in micrometers) and multiply by the test load in grams-force.

3.5.4 Percent Insoluble Matter in Calcium Magnesium Acetate

Currently there is no ASTM method for the determination of insoluble matter in calcium magnesium acetate (CMA). Therefore, a technique was developed by altering ASTM E 534 for the determination of insolubles in sodium chloride. These modifications were based on a technique used by a manufacturer of CMA for product quality control. The modifications to ASTM E 354 are shown in Table 3-7.

TABLE 3-7. MODIFICATIONS TO ASTM E 534-86 TO INCLUDE CALCIUM MAGNESIUM ACETATE (CMA)

The standard ASTM methodology should be used with the following modifications:

8. Preparation of Stock Solution

8.1 Split sample with a riffle to obtain a 100-g sample.

8.2 Weigh out a 30-g sample of material and identify appropriately.

8.3 Place 100 mL of water at a temperature of 37°C (100°F) in the high-speed blender. (Note that a magnetic stirrer may be substituted for the high speed blender.)

8.4 Slowly add the CMA to the blender and blend on slow speed for 1 min.

8.5 Test for water insolubles as described in Sections 17 to 24.

20. Procedure for Calcium Magnesium Acetate

20.1 Transfer the sample prepared in accordance with 8.1 to 8.5 above to a 1-L Erlenmeyer flask, washing out the blender with 100 mL of water (at 37°C) to give a total volume of 200 mL.

20.2 Stir on a magnetic stirrer for 1-h at a constant temperature of 37°C (100°F). Adjust the stirrer speed to give maximum agitation without danger of losing the sampling due to splashing. Place a beaker over the top of the flask while stirring.

20.3 After the 1-h mixing period has elapsed, remove the flask from the magnetic stirrer and allow to cool to room temperature.

20.4 Filter the solution by vacuum through a previously dried (110°C for 1 h) and accurately weighed filter disk using the Parabella funnel. Quantitatively transfer all insoluble matter to the filter paper with distilled water from a wash bottle making sure the sides of the flask are flushed and the rinse allowed to filter.

20.5 Dry the filter disk at 110°C for 1 h and cool in a desiccator. Weigh the disk on an analytical balance to the nearest 0.1 mg.

20.6 Calculate the percent insoluble matter according to Section 22.

SECTION 4

SELECTION CRITERIA

In this section, the potential of antiskid materials to generate PM_{10}, their effectiveness and durability in service, and initial criteria for material selection will be discussed as background to Phase 2. Applicable cost data related to both traditional abrasives and deicers, as well as alternative skid control measures (e.g., embedded pipe pavement heating), have been provided in Appendix I.

4.1 POTENTIAL FOR DUST EMISSIONS

As stated elsewhere in this document, the amount of PM_{10} emitted per vehicle-mile traveled is a direct function of the silt loading on the road surface. Under normal conditions, barring other loading increases such as mud-dirt carryout, a type of loading "equilibrium" is established on the road surface where the amount of new material deposited is balanced with the amount of fines being resuspended as dust. This equilibrium is disturbed, however, when antiskid materials are applied which provide temporary but substantial increases in silt loading and resuspended dust. In this section, applicable data related to silt loading increases and associated ambient air quality impact, due to antiskid materials will be presented.

As determined from available literature, only limited data exist on the air quality impact associated with the application of antiskid materials to paved roadways. Three studies were identified which relate to this topic. One additional study (conducted in Denver during the winter of 1988-1989) was also found, but no firm conclusions could be drawn from the test results.

The first study of interest was conducted in a parking lot in Helena, Montana (Brant, 1972). In this study, a surface sample of sand applied to the parking lot at the end of the winter snow season was collected. The gradation of this sample was compared to that of the original stockpiled material. The results are shown in Figure 4-1.

As can be seen from Figure 4-1, the percentage of material less than 200 mesh (i.e., silt) increased from approximately 2% to approximately 13% over the course of the winter. In addition, the material applied to the parking lot was reported to contain a high percentage of quartz which would indicate good durability characteristics. These results would indicate that even relatively hard, durable material can produce substantial increases in silt loading as a result of vehicular traffic. It should be considered, however,

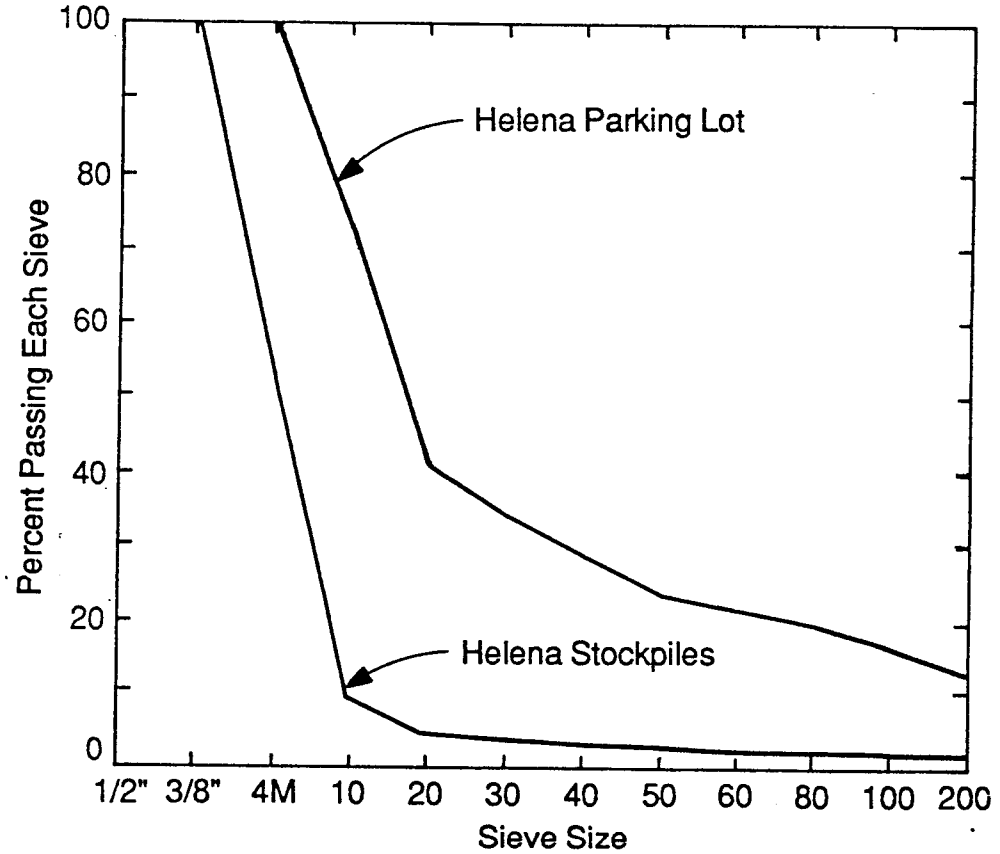


Figure 4-1. Sieve analysis data of antiskid material in Helena parking lot.

that the traffic volume in a parking lot is much lower and traveling at lower speeds than would be the case for a paved city street. Therefore, the increase in silt content observed could be even greater than that reported for the parking lot studied.

The second program considered was a portion of the original MRI paved road study performed in 1977 (Cowherd et al., 1977). In this study, a truck-mounted spreader (similar to that used for winter sanding) was used to artificially load a paved city street with a fine limestone aggregate. The loading and gradation of the surface material were measured for the four exposure profiling tests conducted during the program. Plots of total loading and silt loading vs. number of vehicle passes are presented in Figure 4-2 with the exposure profiling results for total particulate shown in Figure 4-3.

As shown by Figure 4-2, both total loading and silt loading on the road decrease monotonically with vehicle passes after application of limestone gravel fines. This trend is also indicated by the dust concentrations shown in the profiles in Figure 4-3.

The final data set is from the salting and sanding demonstration study performed in Denver during the winter of 1980-1981 (PEDCo, 1981). Two study areas were used. The first study area, located in Lakewood, evaluated the application of salt as compared to the application of sand along 20th Avenue. The second study area evaluated the sanding of two sections of Morrison Road in Denver with and without poststorm street cleaning. Application rates or properties of the antiskid materials used in the study were not specified.

Air quality measurement data collected during the Denver program did not show much correlation with either the application of different antiskid materials or for poststorm cleaning. However, the data from the Lakewood study area were found to be of limited usefulness in defining general trends for the current program.

Figure 4-4 provides a plot of the increase in total surface loading (as related to "baseline" conditions) vs. time after application of sand or salt as calculated by MRI from the raw data. Figure 4-5 shows a similar plot for silt loading. Finally, Figure 4-6 provides air quality measurements for TSP as determined at the near-street monitoring site.

As indicated by these figures, the data are scattered and show a high degree of variability which makes interpretation difficult. However, for sand application there is some limited evidence of air quality improvement that can be associated with an apparent decay in silt loading during the period following sand application.

4.2 EFFECTIVENESS OF ANTISKID MATERIALS

The main purpose of applying abrasives to ice and snow covered roadways is to improve traction or the skid resistance of the surface. The degree to which traction is improved is directly related to the type and properties of the antiskid material and the

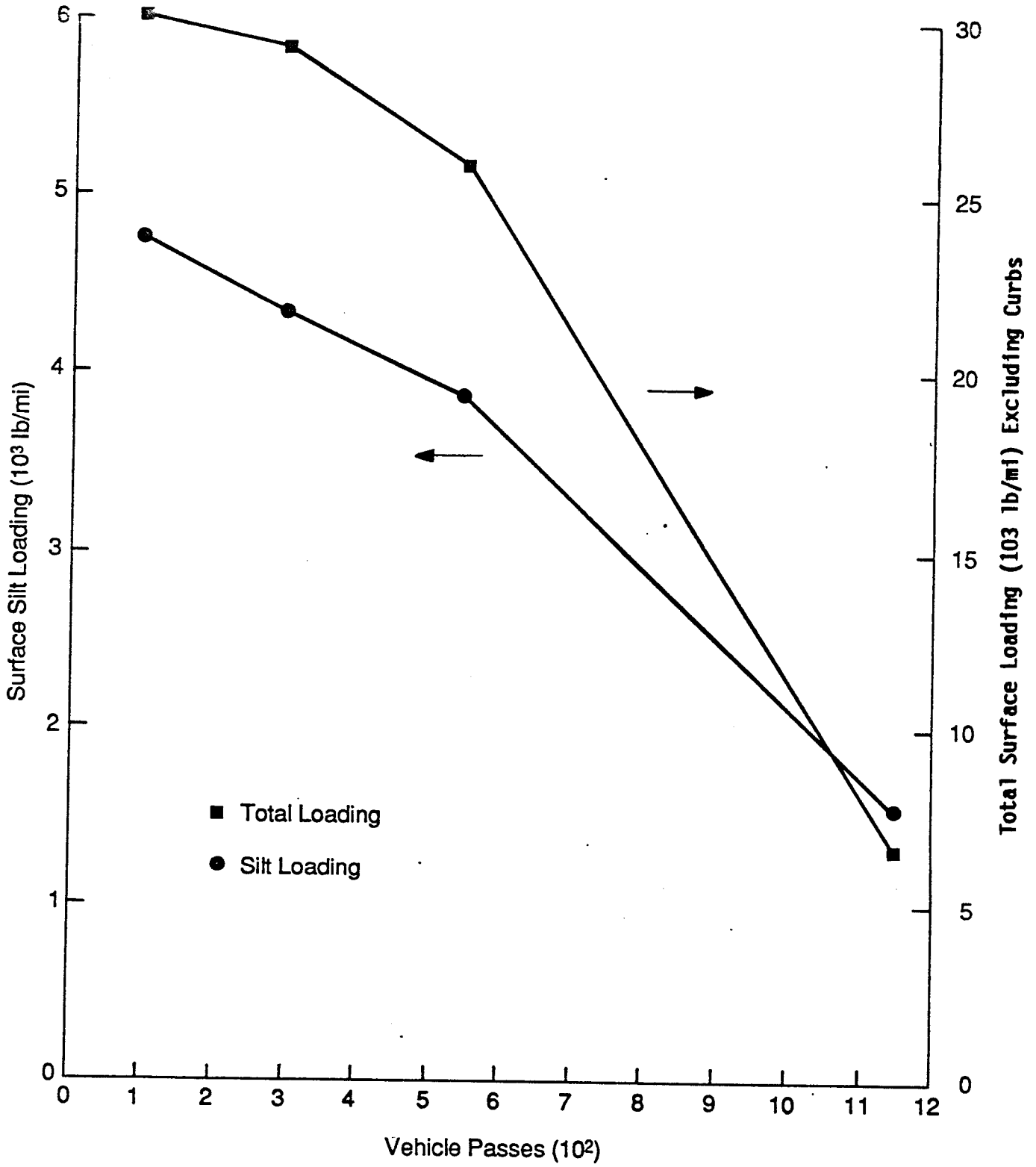


Figure 4-2. Total loading and silt loading vs. number of vehicle passes for artificially loaded paved road.

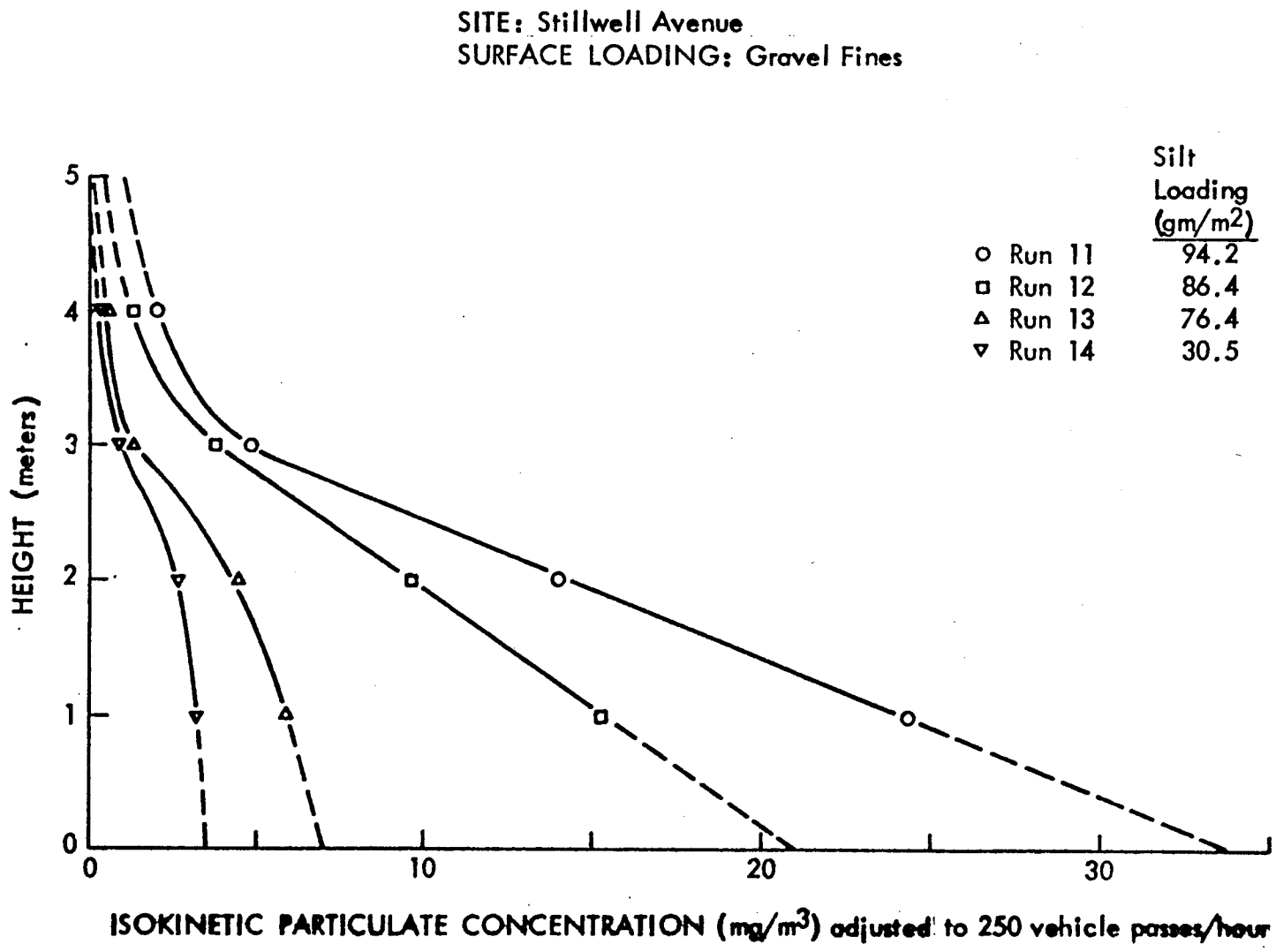


Figure 4-3. Profiles of total particulate concentration for artificially loaded paved road.

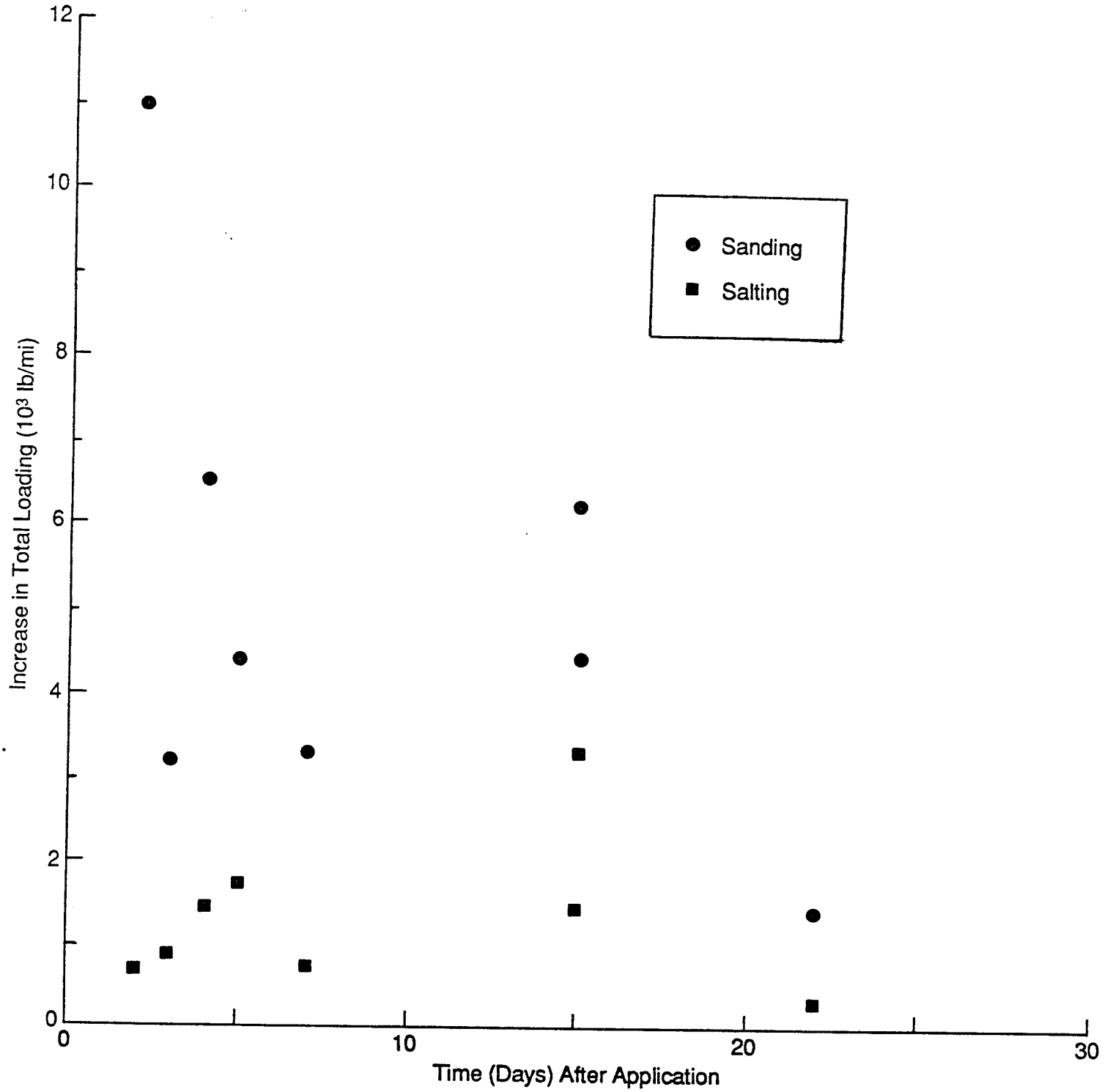


Figure 4-4. Increase in total surface loading vs. time after application of salt or sand.

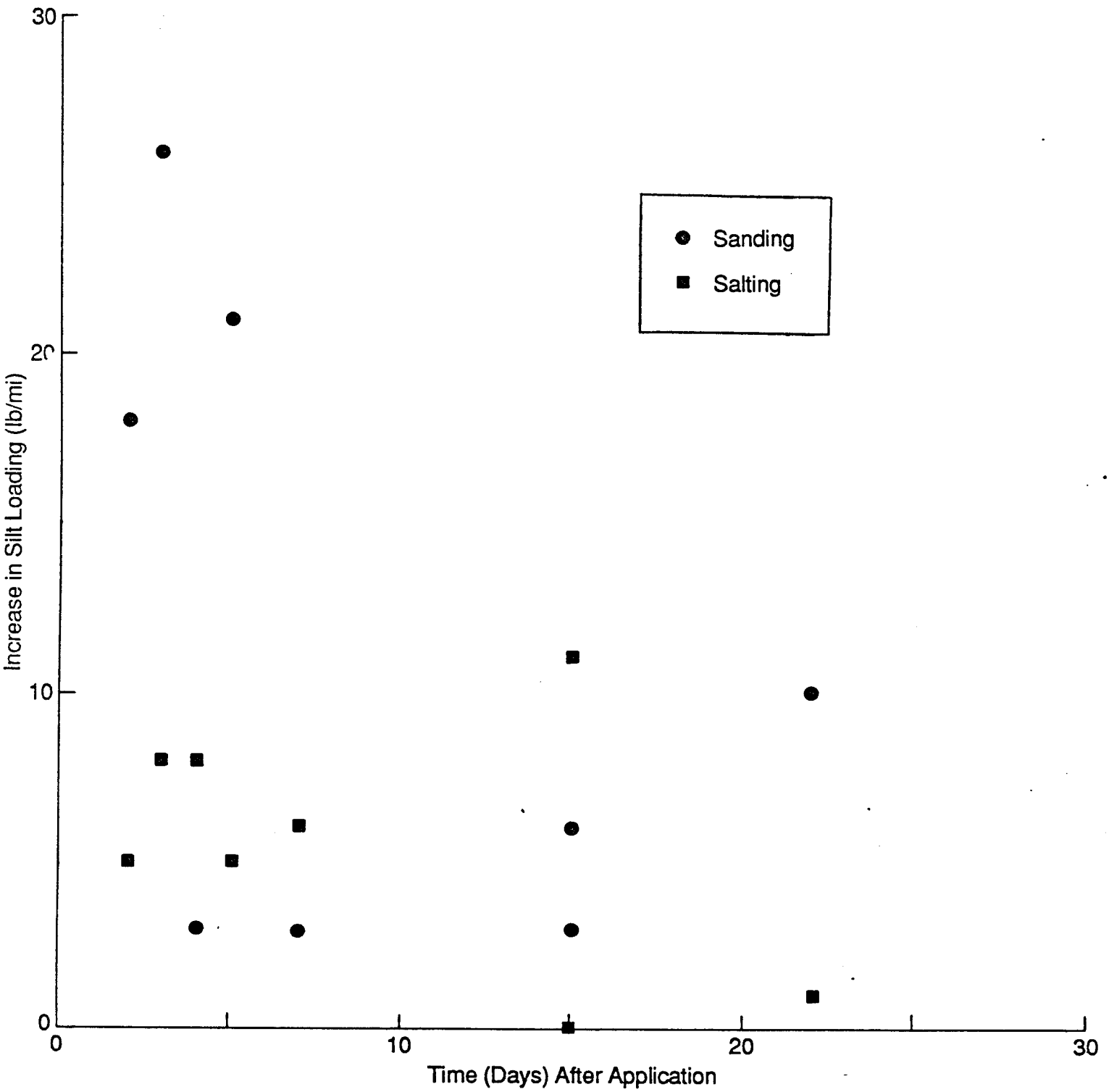


Figure 4-5. Increase in silt loading vs. time after application of salt or sand.

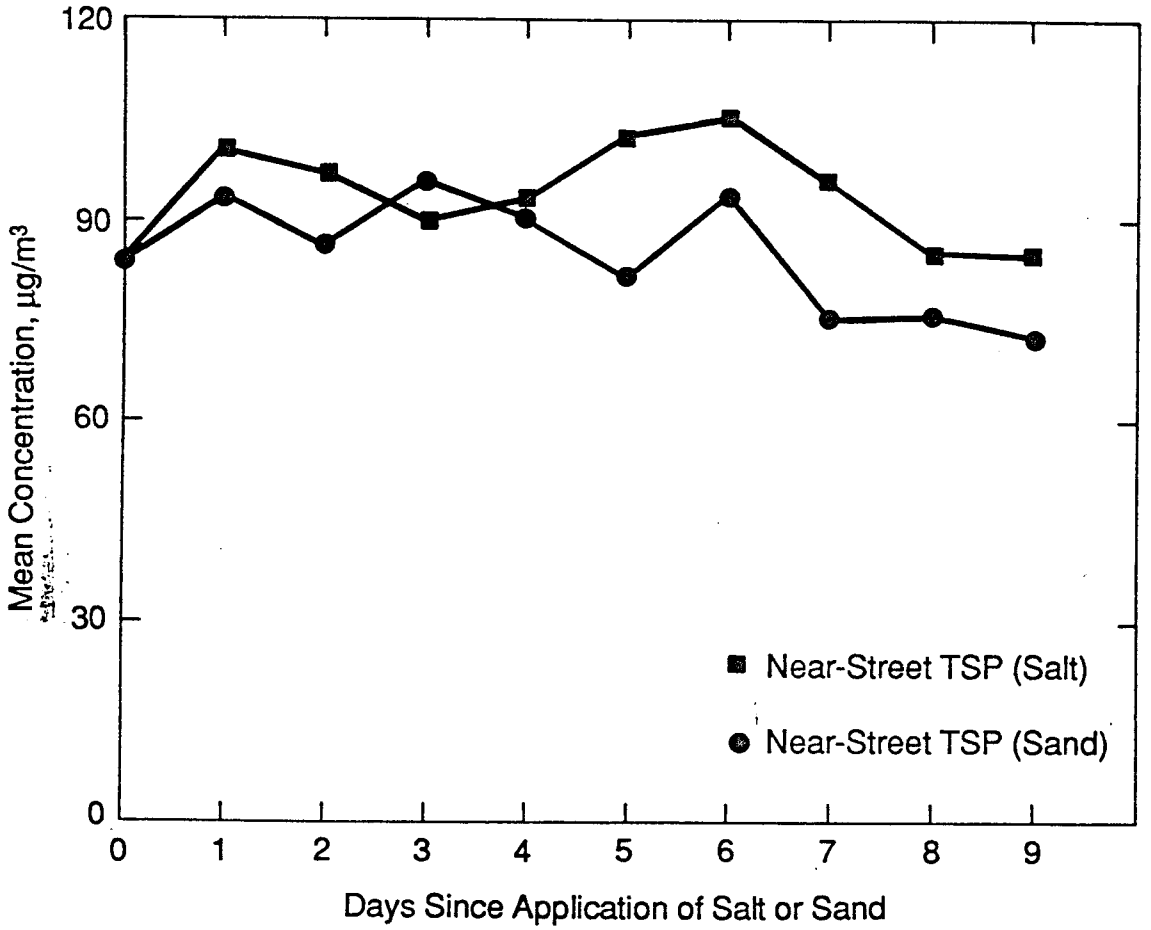


Figure 4-6. TSP air quality impact of salt and sand application over time.

amount of material applied per unit surface area. In this section, the effectiveness of various antiskid materials will be discussed as related to the generation of PM_{10}.

Skid resistance is the force developed between the tire and pavement surface during braking and is a function of: speed; tire temperature, design, and pressure; pavement surface texture; and surface wetness. Frictional force is commonly associated with skid resistance and is mathematically defined as:

$$F = f \times P \tag{4-1}$$

where:
- F = Frictional force
- f = The coefficient of friction
- P = The load perpendicular to the tire/surface interface

Since skid resistance is a function of several independent variables, simple models cannot be used for its measurement. Therefore, most transportation agencies have adopted ASTM Method E 274 which slides a standard locked tire along an artificially wetted (or ice/snow covered) pavement at a constant speed (usually 40 mile/h). The measurements are reported in terms of skid number (SN) which is computed as follows:

$$SN = 100\ f = 100\ T_f/L \tag{4-2}$$

where:
- SN = Skid number at 40 mph
- T_f = Tension force to pull the locked tire across the pavement (lb)
- L = Load (weight) on the tire (lb)

A measure of surface frictional properties can also be determined using the British pendulum tester per ASTM Method E 303. The British pendulum tester is a dynamic pendulum impact-type tester used to measure the energy loss when a rubber slider is propelled over a test surface. The values measured (British Pendulum Number or BPN) represent the frictional properties of the surface not related to other slipperiness measuring equipment.

A number of studies have investigated the ability of various antiskid materials to increase skid resistance or the friction coefficient. Hegmon and Meyer (1968) compared the coefficient of friction of four antiskid abrasives as tested on a circular test track in a cold room. The abrasives tested were: boiler cinders (0.9% < 200 mesh); coke cinders (0.4% < 200 mesh); natural sand (2.6% < 200 mesh); and crushed limestone (0% < 200 mesh). Each material was also subjected to an impact (drop) test of 8,650 ft-lb/ft^2. The test results for the friction measurements conducted are shown in Figure 4-7 (on an equivalent volume basis) and the results of impact tests shown in Table 4-1.

As shown by the above data, sand has the overall highest coefficient of friction and the highest breakdown strength under applied load. Limestone is the second best material with respect to both friction and breakdown strength with cinders being least

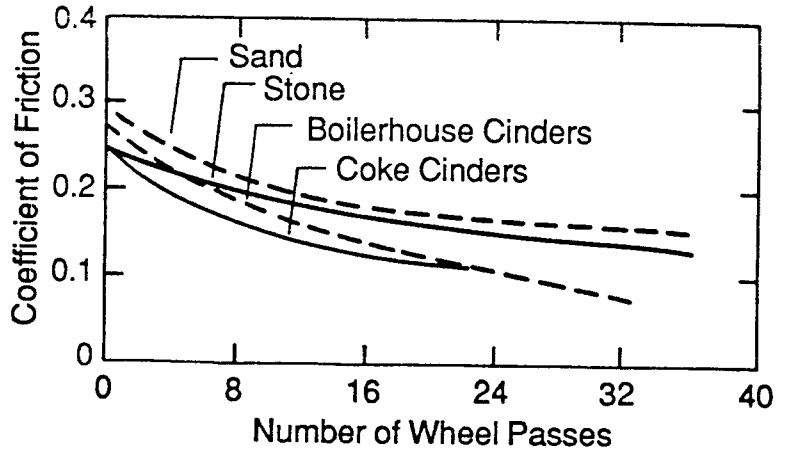


Figure 4-7. Coefficient of friction (f) vs. number of wheel passes for four antiskid materials compared on an equal volume basis.

TABLE 4-1. RESULTS OF IMPACT TESTS

Type of material	Percent breakdown[a]
Boiler cinders	5.3
Coke cinders	3.9
Natural sand	0.7
Limestone	0.8

[a] Breakdown is defined as the percent change in the sum of the cumulative percentages retained on each of the following sieve sizes before and after impact: 3/4 in; 3/8 in; No. 4; No. 8; No. 16; No. 30; No. 50; and No. 100.

acceptable. This study also found that the highest friction coefficients were obtained for materials with gradations between 4 and 16 mesh with finer (i.e., −50 mesh) particles being substantially less effective.

In another study performed by Furbush et al. (1972), pavement skid resistance (no ice or snow) was related to both aggregate mineralogy and particle size. These investigators found that medium to coarse grain sandstones with high levels of quartz exhibited the highest skid numbers (i.e., 65-70 at 40 mph) and soft aggregates such as limestone polish rapidly and exhibit poor skid resistance. These results are illustrated in Figure 4-8 which show the skid resistance of limestone containing various quantities of +200 mesh silica. As shown by these data, the skid resistance increases substantially with increasing silica content. The report also concludes that a Moh Hardness of 5-7 is desirable for good skid resistance.

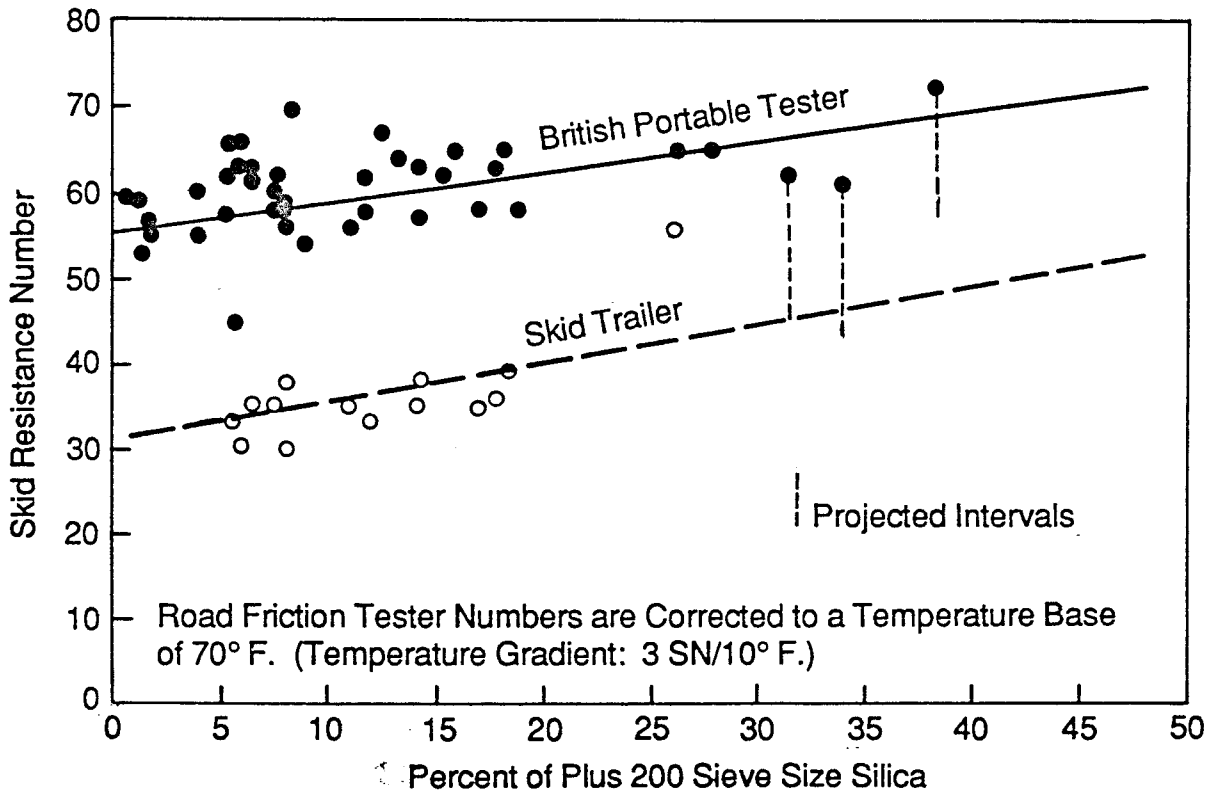


Figure 4-8. Skid resistance of limestone material vs. percent +200 mesh silica (Furbush, 1972).

The final study found in the literature was performed by the State of Alaska (Connor and Gaffi, 1982) to determine optimum specifications for sand used in skid control. This study determined the BPN of different gradations of four types of aggregate material as determined using the British Pendulum Test at various temperatures in a cold room. Vehicle stopping distances on an outdoor ice track were also determined for the same materials. The materials tested were: fractured stone, pit-run stone, concrete aggregate, and coal cinders. The specifications for this material are provided in Table 4-2. Representative data for these tests are shown in Figures 4-9, 4-10, and 4-11 for the cold room and vehicular tests, respectively, at various application rates.

TABLE 4-2. MATERIAL SPECIFICATIONS FOR ALASKA TESTS

Type of material	Percent fracture	Percent < 200 mesh
Fractured stone (Alaska maintenance)	87	1
Pit-run stone	50	0
Concrete aggregate	65	1
Coal ash	—	20

As shown by Figures 4-9, 4-10, and 4-11, the use of coal ash had the highest skid resistance and shortest stopping distance of all the materials tested with concrete sand being a good second choice. Also, the data show that materials in the range of about 16 mesh provided the best skid resistance as compared to coarser materials. Finally, it was also found that angular particles (high percentage of fracture) were more effective than rounded aggregate (e.g., fractured stone vs. pit run).

It should be noted that the coal ash used in the above tests contained a high percentage of < 200 mesh material which would indicate a high potential for PM_{10} production in service. Thus, from an emissions standpoint, coal ash would not be suitable for use in NAAQS nonattainment areas. The above results would indicate, therefore, that a good quality, washed construction aggregate (e.g., sand) would be the best choice with respect to both maximum effectiveness and minimum PM_{10} production of the materials tested.

From the above data it can be seen that the effectiveness of a particular material to increase skid resistance is a function of particle size, shape, hardness, and durability. These results would indicate that a coarse grained (16 to 50 mesh), hard (Moh Hardness 5-7) material with a high degree of angularity (80+% fracture) and durability (< 0.7% impact degradation) would be most appropriate for skid control on ice and snow covered

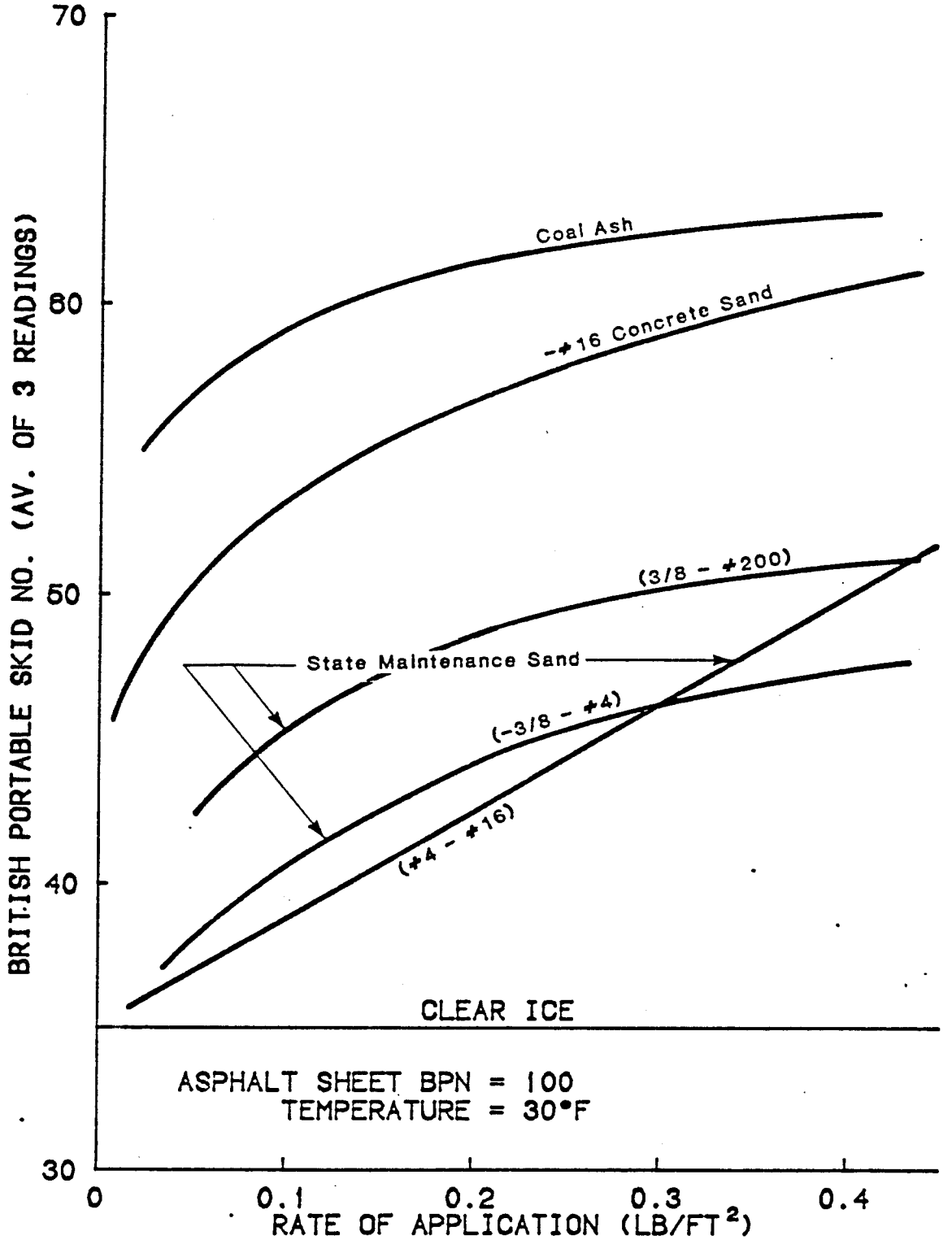


Figure 4-9. Average British portable skid number vs. rate of aggregate application for various antiskid materials (30°F).

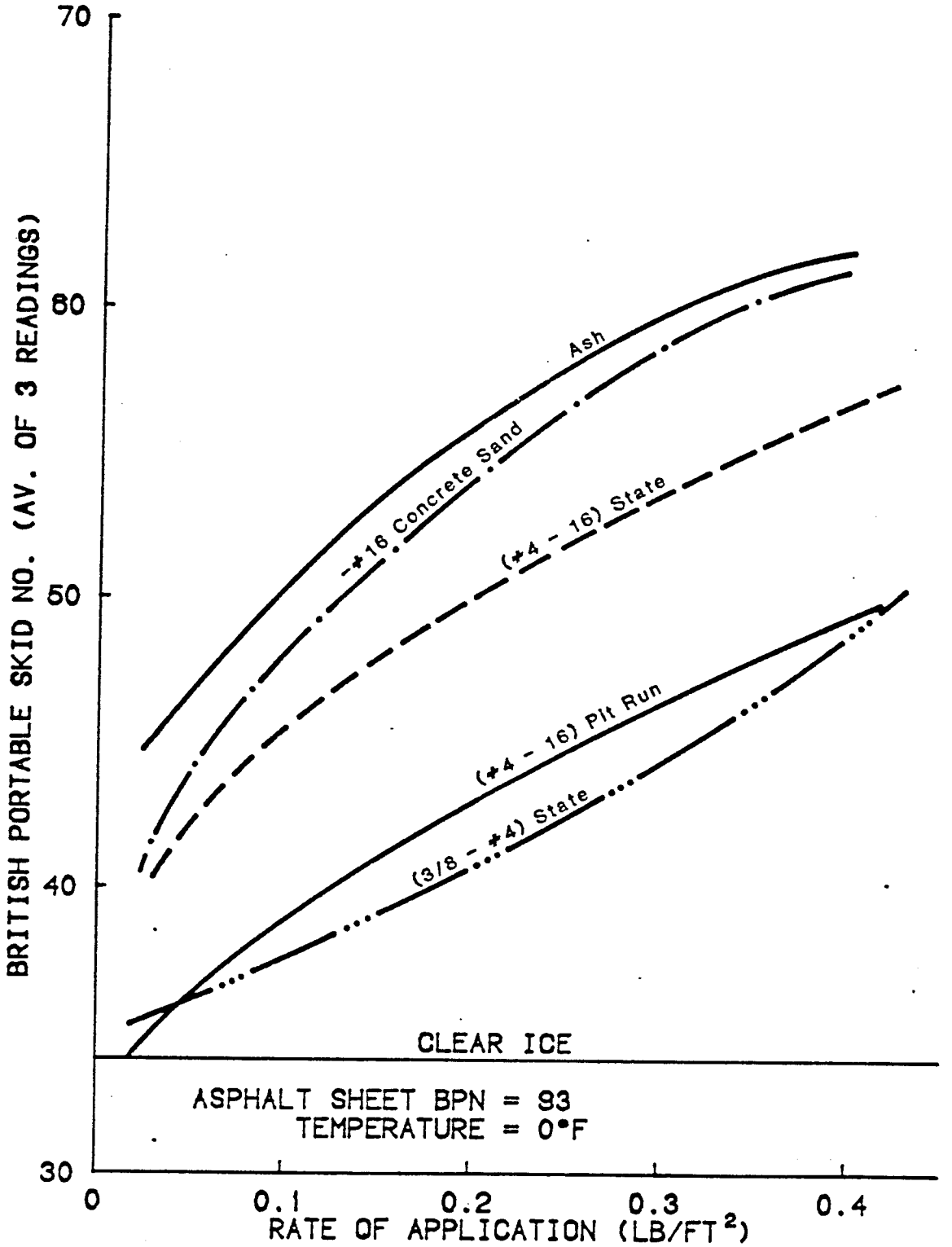


Figure 4-10. Average British portable skid number vs. rate of aggregate application for various antiskid materials (0°F).

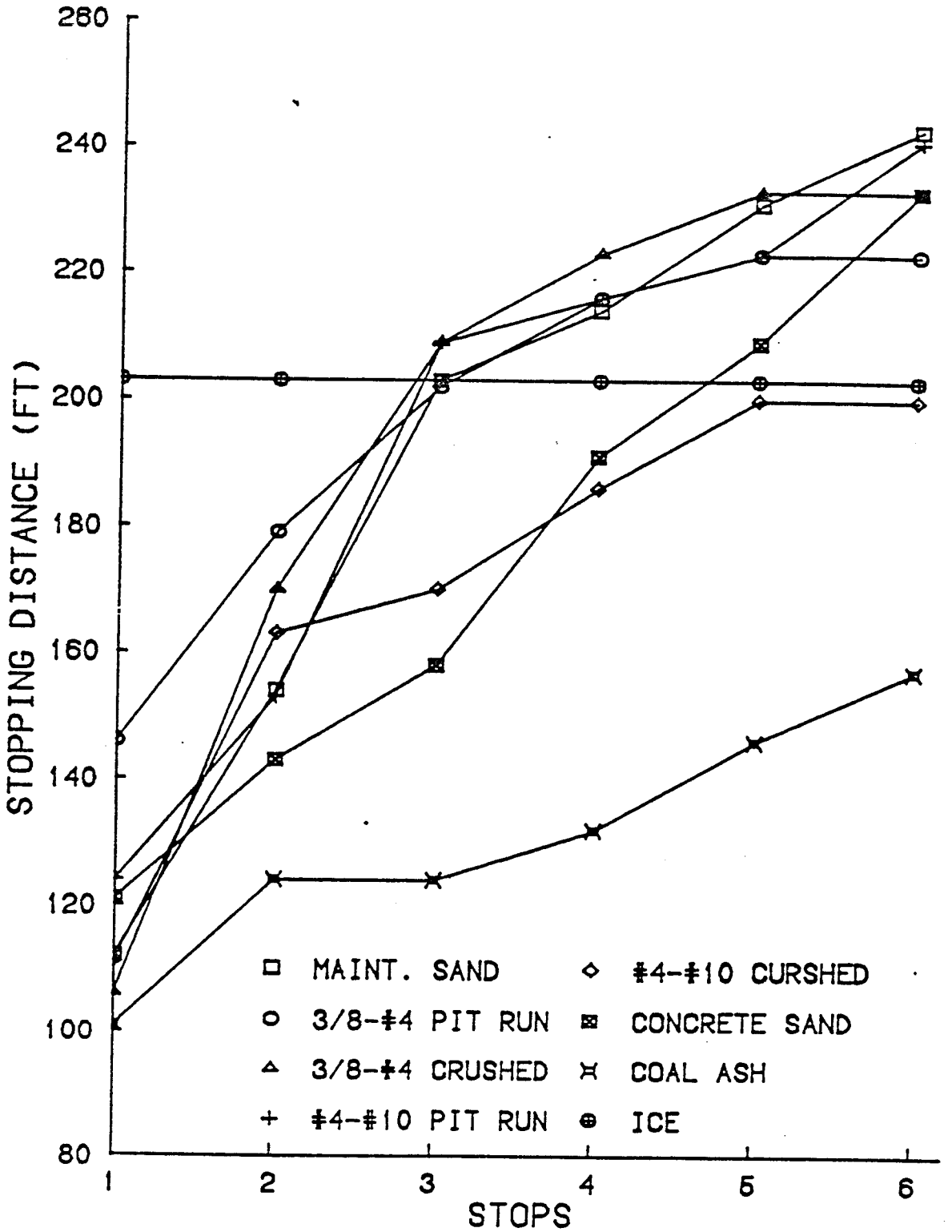


Figure 4-11. Average stopping distances determined on an ice track for various antiskid materials.

roadways. Particle size, shape, and hardness are also related to durability as will be discussed below.

4.3 MATERIAL DURABILITY

As mentioned previously, there were no data located in either the literature search or the telephone survey which relate silt generation (and the associated PM_{10} emissions) with the durability of antiskid materials. All work in this area has focused on construction aggregates used in bituminous and concrete paving mixtures. Although not directly applicable to antiskid abrasives per se, these data can be used to provide guidance in proper material selection. The following discusses the physical and mineral properties of antiskid materials as related to their ability to resist abrasion, impact, and crushing.

4.3.1 Aggregate Physical Properties

The three most important physical properties for good aggregate durability are hardness, particle shape, and particle size. Each is discussed below.

Material hardness is probably the single most important factor in aggregate durability. If a material is very hard it is capable of resisting abrasion, impact, and crushing under applied mechanical loads. Hardness is, of course, a direct function of particle mineralogy as will be presented later.

To determine the effect of hardness on abrasion resistance, controlled experiments were performed by Stiffler (1969) where a mineral surface was wear tested with a commercial abrasive (e.g., SiO_2) through the action of a rolling loaded wheel applied to the specimen. In these tests, Stiffler found that the volume of mineral removed from the surface can be reasonably predicted based on Vickers hardness. The average data collected in the study are shown in Table 4-3.

As shown by the data in Table 4-3, the amount of wear is inversely proportional to the hardness of the mineral. This is illustrated in Figure 4-12 for different minerals abraded with SiO_2. These data would suggest that an antiskid abrasive with a Vickers hardness > ~ 1,000 kg/mm^2 should be acceptable for good durability. [Note that the study performed by Furbush et al. (1972) recommended a Moh Hardness of 5-7 for good skid resistance and the study by Hudec (1984) showed durability increasing with hardness.]

With respect to particle shape, highly angular particles are almost universally recommended for good durability in all applications tested (Dhir et al., 1971; Furbush et al., 1972; Brant, 1972; Anon., 1979; Havens and Newberry, 1982; Connor and Gaffi, 1982). Without detailed petrographic examination, the determination of particle shape is difficult, however.

TABLE 4-3. AVERAGE MINERAL WEAR FOR DIFFERENT ABRASIVE TYPES

Mineral	Melt temp. (°C)	Modulus (psi x 10^6)	Yield stress (psi x 10^4)	Specific gravity	Vickers hardness (kg/mm^2)	Abrasive wear (mm^3 x 10^{-2})		
						Al_2O_2	SiO_2	MgO
$CaCO_3$(c)[a]	825	—	—	2.70	460	42.2	30.7	13.5
$CaCO_3$(i)[b]	825	—	—	2.70	400	38.0	40.9	12.5
Slag	1400	—	—	2.70	620	24.0	16.3	9.4
SiO_2(f)[c]	1700	6	—	2.10	1100	11.0	11.0	2.6
Mullite	1810	21	0.9	2.95	1720	11.0	6.5	3.1
SiO_2(c)[d]	1700	7	0.7	2.65	2000	7.7	6.5	1.7
MgO	2620	42	1.5	3.60	1240	3.4	1.3	0.2
ZrO_2	2650	21	2.0	5.70	1700	2.4	0.6	0.2
SiC	2200	50	5.0	3.00	4500+	0.7	0.4	0.07
Al_2O_3	2000	45	4.0	4.00	3300	0.3	0.7	0.03

[a] Crystallike with cleavage planes.

[b] Limestone chips.

[c] Clear fused-quartz rod.

[d] Glasslike lump.

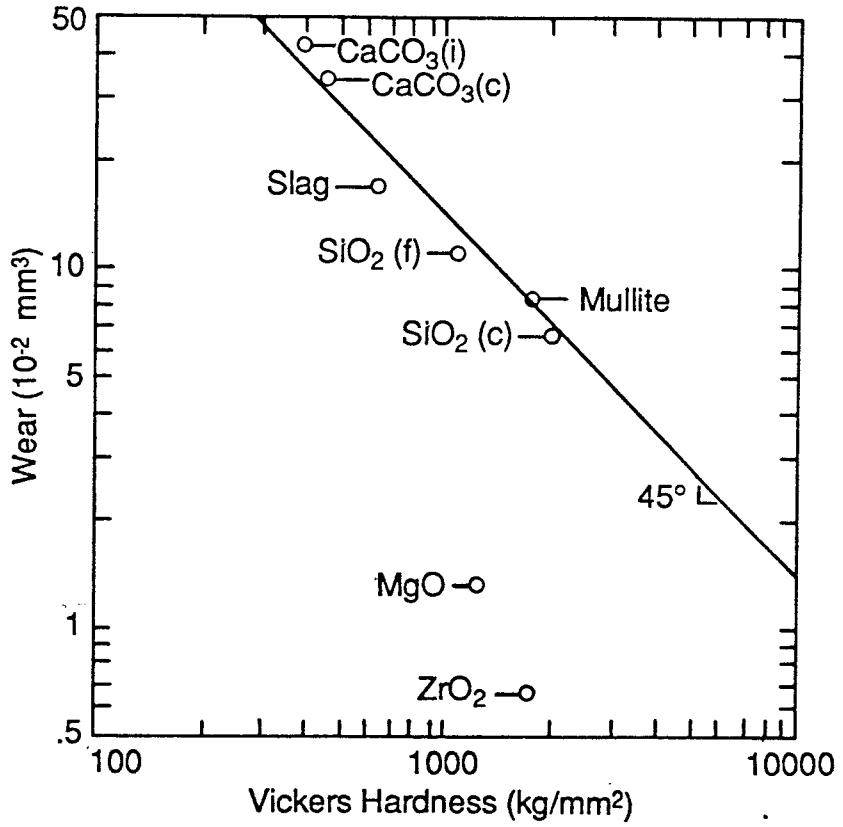


Figure 4-12. Mineral wear rate vs. Vickers hardness for SiO_2 abrasive.

Havens and Newberry (1982) determined that the shape of aggregate particles can be determined indirectly from the measurement of void fraction using a version of ASTM Method C-29 (see Section 3.3). They found that a void fraction > 50% indicates a greater degree of disorder in particle shape and/or texture and thus is indicative of angular particles. Also, Connor and Gaffi (1982) found that a minimum fracture of 80% on one face for the material retained on the No. 10 sieve should be adequate for good skid resistance.

The final physical property of importance in aggregate durability is particle size. As stated in Section 3, Hudec (1984) determined that the durability of an aggregate material (as determined by petrography) decreases with grain size. This is illustrated by the relationship provided in Equation (3-3). When effectiveness is also considered (see Section 5.2 above), particle sizes in the range of about 16 mesh seem to be exhibit the highest skid resistance. It would seem that this specification would also be applicable to good durability as well.

4.3.2 Particle Mineralogy

The hardness of an aggregate material is directly related to its mineralogy. Numerous studies have investigated particle mineralogy with respect to durability in paving mixtures (Dhir et al., 1971; Furbush et al., 1972; Anon., 1979; Woodside and Peden, 1983; Hudec, 1984; Goswami, 1984; Dubberke and Marks, 1985). These studies have shown that aggregates containing high percentages of siliceous minerals such as quartz, granite, chert, greywacke, etc., show the highest durability with respect to abrasion, impact, and crushing (Stiffler, 1969; Anon., 1979; Hudec, 1984; Goswami, 1984).

To produce durable pavement mixtures, many transportation agencies have adopted standards for aggregates which include minimum contents of various minerals. For example, the State of Kentucky has specified a minimum quartz content of sand to be 90% by visual count (e.g., ASTM Method C-295) or 94% by chemical analysis (Havens and Newberry, 1982). Also, the U.S. Transportation Research Board (TRB) has established a durability classification system for aggregates used in pavement mixtures with respect to skid resistance. These classifications are as follows (Anon., 1979):

- Group I—Outstanding Polish Resistance. Aggregates in this group are heterogeneous combinations of hard minerals with a coarse-grained microstructure of hard particles bonded together with a slightly softer matrix. Examples include emery or industrial abrasives which are normally too expensive for use in road pavement mixtures.

- Group II—Above Average Polish Resistance. This group comprises a minority of aggregate types used for highway paving, including blast furnace slags, expanded shales, and crushed sedimentary rocks such as sandstone, arkose, greywacke, and quartzite. Recommended for use on high traffic volume roads.

- Group III—Average Polish Resistance. This group consists of aggregates currently used in pavement construction, including crushed, dense igneous and metamorphic rocks of the granite, granite gneiss, and diorite types. Exhibits satisfactory skid resistance for all but the most severe conditions.

- Group IV—Below Average Polish Resistance. All remaining aggregate mineral types, except for Group V. Acceptable for use on low volume pavement surfaces and where skid resistance requirements are below normal.

- Group V—Low Polish Resistance. Typical of this group are the carbonate minerals containing low levels of siliceous materials and uncrushed gravels.

Based on the above information, it can be concluded that aggregates used for skid control purposes should be a Group III material or better (according to the TRB classification) with a silica content of around 90%. These specifications should assure a highly durable material with a low tendency for fines generation when exposed to vehicular traffic. (Note, however, that some transportation agencies use aggregate rejected for use in pavement as antiskid materials.)

4.3.3 Resistance to Abrasion, Impact, and Crushing

The ability of an aggregate to withstand the effects of abrasion, impact, and crushing is a function of the material properties discussed above. Therefore, as a measure of resistance to these effects, a number of standard tests have been developed as discussed previously in Section 3. Based on MRI's analysis of the available literature, it was found that the Los Angeles abrasion test is probably the best overall indicator of aggregate durability for antiskid abrasives. This is illustrated below.

With respect to overall durability of construction aggregates, the work performed by Woodside and Peden (1983) contains the most comprehensive comparison of aggregate properties found in the literature. In this work, 13 aggregate samples were evaluated for 10 different strength parameters. Using this data set, MRI performed a multiple linear regression analysis of selected parameters to determine their relationship to the applicable Los Angeles abrasion value:

$$LAAV = 11.9 + 0.611\ ACV + 1.10\ AIV + 0.0209\ S - 0.0837\ F - 0.481\ W - 6.06\ SG \quad (4\text{-}5)$$

where:

LAAV	=	Los Angeles abrasion value (per ASTM C 131)
ACV	=	Aggregate crushing value, % (per British Standard 812)
AIV	=	Aggregate impact value, % (per British Standard 812)
S	=	Soundness, % (per ASTM C 88)
F	=	Flakiness, % (per British Standard 812)
W	=	Water absorption, % (per British Standard 812)
SG	=	Specific gravity (per British Standard 812)

The correlation coefficient for the above regression is 0.990; this result indicates that the combination of the six strength parameters are highly related to the Los Angeles abrasion value. Thus, these results indicate that a single test can reasonably be used as an overall measure of aggregate durability. It was therefore concluded that Phase 2 of the program should include the determination of durability using the Los Angeles Abrasion Method and that the results of this test be used to compare different aggregate samples as related to silt generation under simulated traffic conditions.

4.4 INITIAL ACCEPTABILITY CRITERIA

Based on an engineering evaluation of information obtained from the literature search and telephone survey, initial selection criteria have been developed for antiskid materials that have a low target potential for silt generation in service. For example, these criteria can probably be met by a washed construction aggregate (sand). Selection of less durable abrasives because of cost/availability considerations would entail higher PM_{10} emissions unless mitigated by more extensive cleanup procedures. These criteria are provided only as preliminary guidelines pending further laboratory evaluations in Phase 2 (see Section 6). The acceptability criteria derived from available data are shown in Table 4-4.

TABLE 4-4. ACCEPTABILITY CRITERIA FOR ANTISKID MATERIALS

Type of material	Material or application parameter	Recommended value
Abrasives	General gradation	> 16 mesh
	Silt content as applied	< 1%
	Moh hardness	5-7
	Vickers hardness	> 1,000 kg/mm^2
	Fracture	> 80%
	Void fraction	> 50%
	Quartz content	> 90%
Salts	Percent insoluble matter	< 2%

SECTION 5

MATERIALS EVALUATION

Two different sample sets were evaluated in the program to develop a data base for typical antiskid materials. The first set consisted of aggregate materials commonly used in construction or readily available by-products of other processes. In the second set were materials used for ice and snow control in PM_{10} nonattainment areas.

The following sections describe origin of the samples obtained and their physical properties. Analysis of physical parameters resulted in the definition of five distinct groupings (or clusters), which were used to select suitable samples for traffic tests in MRI's cold room.

5.1 ORIGIN OF MATERIAL SAMPLES

The first sample set consisted of six different construction and by-product materials. Five of these materials were obtained from local sources with the remaining sample provided by a state regulatory agency. These samples were used for both a laboratory evaluation of the modified test methods described in Section 3.5 and simulated traffic tests. The first samples consisted of: calcium magnesium acetate (CMA); road salt (i.e., NaCl); ice control sand; crushed limestone; power plant bottom ash; and river rock from Presque Isle, Maine. These samples are described in Table 5-1 along with the quantities received.

In the second set of samples were 28 different materials obtained from state and local regulatory agencies located in PM_{10} nonattainment areas. These samples consisted of a wide range of natural and manmade aggregates available in their local jurisdiction.

Of the original 34 materials, 28 were finally selected by the EPA Work Assignment Manager (WAM) for physical/chemical analysis in the program. An inventory of the materials received along with those selected for analysis are also shown in Table 5-1.

5.2 MATERIAL PROPERTIES

Each material in both sample sets were analyzed for up to nine different properties, as applicable. These properties included: Los Angeles abrasion loss; wet aggregate durability; quartz content; silt content; Vickers hardness; unit weight; void fraction; particle shape index; and percent insoluble matter. Table 5-2 provides the ASTM

TABLE 5-1. SAMPLE INVENTORY

Sample origin	Sample designation	Quantity received	Sample properties
Chevron Chemicals	Calcium magnesium acetate[a]	50 lb	Round pellets
Missouri Dept. of Trans. (DOT)	Road salt[a]	3 x 75 lb	Carey salt in piles
Holiday Sand & Gravel	Ice control sand[a]	2 x 100 lb	Washed river sand; < 0.1% silt
Astro Quarries	Crushed limestone[a]	2 x 70 lb	Nominal 1/4 in
Nearman Power Plant, Kansas	Bottom ash[a]	3 x 50 lb	Cinders from Wyoming coal
Maine DEP	Maine DOT[a]	2 x 65 lb	Presque Isle stockpile; "dirty" sand
	Presque Isle[b]	2 x 55 lb	City stockpile; cleaner and more durable
Colorado APCD	Department of Health[b]	2 x 100 lb	Washed squeege; 3/8 in nominal
Wyoming DEQ	Scoria-Sheridan[b]	2 x 200 lb	Dark red material
	Washed-Sheridan[b]	2 x 200 lb	Washed sand; 95% > 3/8 in; 2% to 7% silt; wear % < 35
Montana Dept. of Health & Environmental Services	Kalispell—new[b]	65 + 75 lb	Washed and screened
	Kalispell—old	73 lb	Pit run material

(continued)

TABLE 5-1 (continued)

Sample origin	Sample designation	Quantity received	Sample properties
Montana Dept. of Health & Environmental Services	Kalispell—2 yr old[b]	72 lb	Pit run material
	Kalispell Dept. of Highways	90 + 80 lb	Pit run material
	Libby, Montana, St. Hwy. Shop[b]	56 + 48 lb	Pit run material; screened
	Libby, Montana, County Shop	48 + 56 lb	Pit run; screened to 1 in
	Libby, Montana, City Sand[b]	70 + 69 lb	Pit run material; screened
	Libby, Montana, City Crush[b]	57 + 68 lb	Crushed and screened to ½ in
	Columbia Falls—Old[b]	60 + 61 lb	Pit run material
	Columbia Falls—New[b]	65 + 63 lb	Washed and screened
	Missoula City—90	70 + 100 lb	Wet durability > 70; < 3% silt
	Missoula City—pre 1987[b]	~ 100 lb	Unknown
	Missoula—Montana State Hwy.	~ 100 lb	4% to 10% silt
	Missoula County—90[b]	~ 100 lb	< 6% passing No. 100 screen

(continued)

TABLE 5-1 (continued)

Sample origin	Sample designation	Quantity received	Sample properties
Montana Dept. of Health & Environmental Services	Butte/Silver Bow City/County Sand Pile[b]	2 x 50 lb	Pit run material
	Ronan City Sand[b]	150 lb	Pit run material
	MDOH—Nine Pipes[b]	150 lb	Reject paving material
	BIA—Lame Deer	200 lb	Unknown
	St. Xavier[b]	100 lb	Reject paving material
City of Thompson Falls, Montana	Shipping Nos. 301663, 301674, and 301685[b]	54 + 49 + 70 lb	Pit run material
City of Steamboat Springs, Colorado	Sand[b]	~ 50 lb	"Coarse" sand
	Sand[b]	~ 50 lb	"Fine" sand
	Squeege[b]	2 x 50 lb	Unknown
	Scoria[b]	2 x 30 lb	Unknown

[a] Samples split and analyzed during laboratory evaluation.

[b] Samples split and analyzed during materials evaluation.

TABLE 5-2. APPLICABLE TEST METHODS FOR ANTISKID MATERIALS

Type of material	Material property	ASTM method	Method modified[a]
Abrasives	LA abrasion loss[b]	C 131	Yes
	Wet durability[b]	D 3744	No
	Quartz content[b]	C 289	No
	Silt content[c]	C 136	Yes
		C117	Yes
	Vickers hardness[d]	E 384	Yes
	Void fraction[b]	C 29	No
		C 128	No
	Particle shape and texture[b]	D 3398	No
Deicers	Insoluble matter—NaCl[c]	E 534	No
	Insoluble matter—CaMg acetate[c]	E 534	Yes

[a] See Section 3.5 for discussion of modified ASTM methods.

[b] Analyses performed by commercial testing laboratories.

[c] Analyses performed by MRI. CaMg acetate = calcium magnesium acetate (CMA).

[d] Analyses performed by Dr. Dick Hagni, University of Missouri-Rolla.

methods used for each analysis along with an indication of whether the method was modified for application to antiskid materials.

The test data obtained for both sample sets are provided in Tables 5-3 and 5-4. For cases where a modified ASTM method is used, Table 5-3 shows the results of triplicate analyses performed on the first set of six materials. Also noted in these tables are materials selected for further testing under simulated traffic conditions in MRI's cold room.

For those samples where triplicate analyses were performed, range percent is provided as a measure of method precision. As shown in Table 5-5, the "best" and "worst" precision was obtained for the same test—LA abrasion loss. The results indicate that additional development is probably needed on this method as well as the other methods to improve reproducibility.

5.3 MATERIALS CLASSIFICATION ANALYSIS

The laboratory data generated in this study were subjected to exploratory statistical analysis techniques. The effort was guided by two general questions. These are:

1. For the 25 materials considered in this program, do the physical parameters (i.e., material properties) exhibit significant interrelationships?

2. If the material properties show significant intercorrelation, can these relationships be used to define distinct material types?

These questions were addressed using linear correlations as well as multivariate pattern recognition techniques—principal components analysis (PCA) and cluster analysis. Details of these techniques can be found in many standard statistical texts. The following concentrates on presentation of the results indicated by application of each of the techniques to the data sets developed in this study.

5.3.1 Linear Correlation—Material Properties

Table 5-6 presents the correlation matrix of material properties; it is based on the laboratory data for the 25 materials (see Tables 5-3 and 5-4). (Note: Both deicers and limestone were eliminated from this analysis.) Examination of the matrix indicates two main points. First, there apparently is a set of interrelationships between material silt content and the corresponding abrasion and wet durability scores. The positive correlation between silt and abrasion suggests that materials with high silt content will readily abrade (i.e., produce substantial additional "fines" when subjected to mechanical forces found in the LA abrasion machine). Of course, the linear correlation also implies that the opposite condition—low silt content, low abrasion—holds true. Figure 5-1 presents a scatterplot of the correlation between silt content and the abrasion index.

TABLE 5-3. RESULTS OF LABORATORY EVALUATION

Material sample	Los Angeles abrasion loss (wt. %)[a]	Wet aggregate durability index[b]	Quartz content[c] (mmol/L)	Silt content (wt. %)[d]	Vickers hardness (kg/mm^2)[e]	Unit weight (kg/m^3)[f]	Void fraction (wt. %)[f]	Particle shape index[g]	Insoluble matter (%)[h]
Washed construction sand (Holiday S&G ice control sand)[i]									
• Sample 1	0.90	95	26.1	0.02	1,238	1,799	30.2	6.3	NA
• Sample 2	1.43	—	—	—	798	—	—	—	NA
• Sample 3	1.66	—	—	—	755	—	—	—	NA
• Average	1.33	—	—	—	930	—	—	—	NA
Maine DOT Presque Isle stockpile[i]									
• Sample 1	8.35	60	19.6	4.31	928	1,659	23.1	8.1	NA
• Sample 2	8.04	—	—	—	775	—	—	—	NA
• Sample 3	7.10	—	—	—	859	—	—	—	NA
• Average	7.83	—	—	—	854	—	—	—	NA
Crushed limestone									
• Sample 1	7.03	43	None detected	1.56	85.5	1,497	40.3	12.1	NA
• Sample 2	7.83	—	—	—	105	—	—	—	NA
• Sample 3	7.06	—	—	—	93	—	—	—	NA
• Average	7.31	—	—	—	95	—	—	—	NA
Boiler bottom ash (cinders)									
• Sample 1	7.21	68	39.4	4.41	343	1,223	46.0	21.1	NA
• Sample 2	7.21	—	—	—	258	—	—	—	NA
• Sample 3	7.42	—	—	—	428	—	—	—	NA
• Average	7.28	—	—	—	343	—	—	—	NA

(continued)

TABLE 5-3 (continued)

Material sample	Los Angeles abrasion loss (wt. %)[a]	Wet aggregate durability index[b]	Quartz content[c] (mmol/L)	Silt content (wt. %)[d]	Vicker's hardness (kg/mm^2)[e]	Unit weight (kg/m^3)[f]	Void fraction (wt. %)[f]	Particle shape index[g]	Insoluble matter (%)[h]
MO DOT road salt[i]									
• Sample 1	0.66	NA	NA	0.02	NA	NA	NA	NA	0.58
• Sample 2	—	NA	NA	—	NA	NA	NA	NA	0.50
• Sample 3	—	NA	NA	—	NA	NA	NA	NA	1.23
• Average	—	NA	NA	—	NA	NA	NA	NA	0.77
Calcium magnesium acetate (CMA)									
• Sample 1	0.30	NA	NA	0.02	NA	NA	NA	NA	2.03
• Sample 2	0.31	NA	NA	—	NA	NA	NA	NA	1.72
• Sample 3	—	NA	NA	—	NA	NA	NA	NA	1.86
• Average	0.30	NA	NA	—	NA	NA	NA	NA	1.87

a Per modified ASTM Method C-131.

b Dimensionless. Per ASTM Method D-3744.

c Per ASTM Method C-289.

d Silt = % < 200 mesh or 75 μmP. Per ASTM Methods C-136 and C-117 as modified by MRI.

e Per modified ASTM Method E-384. Average of 20 indentations per polished section. NA = not applicable.

f Per ASTM Methods C-29 and C-128. NA = not applicable.

g Dimensionless. Weighted average per ASTM Method D-3398. NA = not applicable.

h Road salt (NaCl) per ASTM E-584. CMA per modified ASTM E-584. NA = not applicable.

i Samples exposed to simulated traffic.

TABLE 5-4. RESULTS OF MATERIALS EVALUATION

Material sample	Los Angeles abrasion loss (wt. %)[a]	Wet aggregate durability index[b]	Quartz content[c] (mmol/L)	Silt content (wt. %)[d]	Vickers hardness (kg/mm^2)[e]	Unit weight (kg/m^3)[f]	Void fraction (wt. %)[f]	Particle shape index[g]
Presque Isle, Maine—City Stockpile	4.01	68	17.4	1.24	88.7	1,750	342.8	11.9
Colorado APCD—Washed Squeege[h]	3.84	97	15.9	0.09	1,042	1,627	36.4	15.5
Sheridan, Wyoming—Scoria[h]	13.1	90	155.3	4.90	607	1,348	33.2	12.7
Sheridan, Wyoming—Washed Sand	5.83	94	10.0	1.82	443	1,789	32.4	15.3
Kalispell, Montana—"New"	5.49	68	36.5	0.99	148	1,651	32.8	11.1
Kalispell, Montana—"Old"	7.06	45	29.1	6.82	1,052	1,863	25.4	12.8
Libby, Montana—State Highway Shop	7.82	72	28.9	3.56	465	1,776	29.7	8.67
Libby, Montana—City Sand	6.51	86	31.6	4.91	840	1,916	26.5	8.07
Libby, Montana—City Crushed Aggregate	6.41	75	22.7	3.02	676	1,633	38.5	21.2
Columbia Falls, Montana—"Old"	6.30	78	33.8	1.97	955	1,784	26.5	10.7
Columbia Falls, Montana—"New"[h]	3.62	63	32.5	2.47	765	1,641	36.5	20.5
Missoula, Montana—County 1990	5.60	62	34.4	1.77	280	1,698	34.6	17.6
Missoula, Montana—Pre-1987	17.1	56	22.6	5.26	755	1,654	33.0	6.5
Butte/Silver Bow, Montana—City/County Sand Pile	5.85	85	11.4	1.43	620	1,656	30.9	13.6
St. Xavier, Montana	3.62	87	187.8	4.14	828	1,683	33.1	14.6
Thompson Falls, Montana	11.6	56	27.5	8.93	689	1,816	26.1	11.3
Steamboat Springs, Colorado—"Coarse" Sand[h]	3.95	85	34.2	0.25	554	1,669	33.2	8.6
Steamboat Springs, Colorado—"Fine" Sand	3.89	78	22.3	1.22	493	1,715	33.2	10.2

(continued)

TABLE 5-4 (continued)

Material sample	Los Angeles abrasion loss (wt. %)[a]	Wet aggregate durability index[b]	Quartz content[c] (mmol/L)	Silt content (wt. %)[d]	Vicker's hardness (kg/mm^2)[e]	Unit weight (kg/m^3)[f]	Void fraction (wt. %)[f]	Particle shape index[g]
Steamboat Springs, Colorado—Squeege	6.49	80	31.6	1.17	503	1,651	34.7	14.2
Steamboat Springs, Colorado—Scoria[h]	8.72	100	39.9	2.28	458	856	45.1	27.4
Ronan, Montana—City Sand	10.7	73	26.3	4.99	408	1,855	27.5	8.95
MDOH—Nine Pipes	8.24	72	32.2	4.21	1,163	1,742	30.2	10.3

a Per modified ASTM Method C-131.

b Dimensionless. Per ASTM Method D-3744.

c Per ASTM Method C-289.

d Silt = % < 200 mesh or 75 μmP. Per modified ASTM Method C-136.

e Per modified ASTM Method E-384. Average of 20 indentations per polished section.

f Per ASTM Methods C-29 and C-128.

g Dimensionless. Weighted average per ASTM Method D-3398.

h Samples exposed to simulated traffic.

TABLE 5-5. RANGE PERCENT VALUES FOR MODIFIED ASTM METHODS

Parameter	Sample identification	Range percent[a]
LA abrasion loss	Washed construction sand	57.1
	Maine DOT Presque Isle	16.0
	Crushed limestone	10.9
	Boiler bottom ash (cinders)	2.9
Vickers hardness	Washed construction sand	51.9
	Maine DOT Presque Isle	17.9
	Crushed limestone	20.5
	Boiler bottom ash (cinders)	49.6
Insoluble matter	Calcium magnesium acetate	16.6

[a] Range *percent* = $\frac{\textit{high value} - \textit{low value}}{\textit{mean value}} \times 100$

TABLE 5-6. LINEAR CORRELATION COEFFICIENTS (r)—MATERIAL PROPERTIES

Material property	LA abrasion	Wet aggregate durability index	Quartz content	Silt content	Vickers hardness	Unit weight	Void fraction	Particle shape index
LA abrasion loss	1.0							
Wet aggregate durability	−0.34	1.0						
Quartz content	0.09	0.23	1.0					
Silt content	0.68[a]	−0.55[a]	0.21	1.0				
Vickers hardness	−0.06	0.07	0.06	0.18	1.0			
Unit weight	−0.16	−0.35	−0.25	0.12	0.29	1.0		
Void fraction	−0.11	0.32	0.09	−0.34	−0.38	−0.84[a]	1.0	
Particle shape index	−0.13	0.18	0.08	−0.11	−0.27	−0.72[a]	0.79[a]	1.0

[a] Underlined coefficients significant beyond the 99% level.

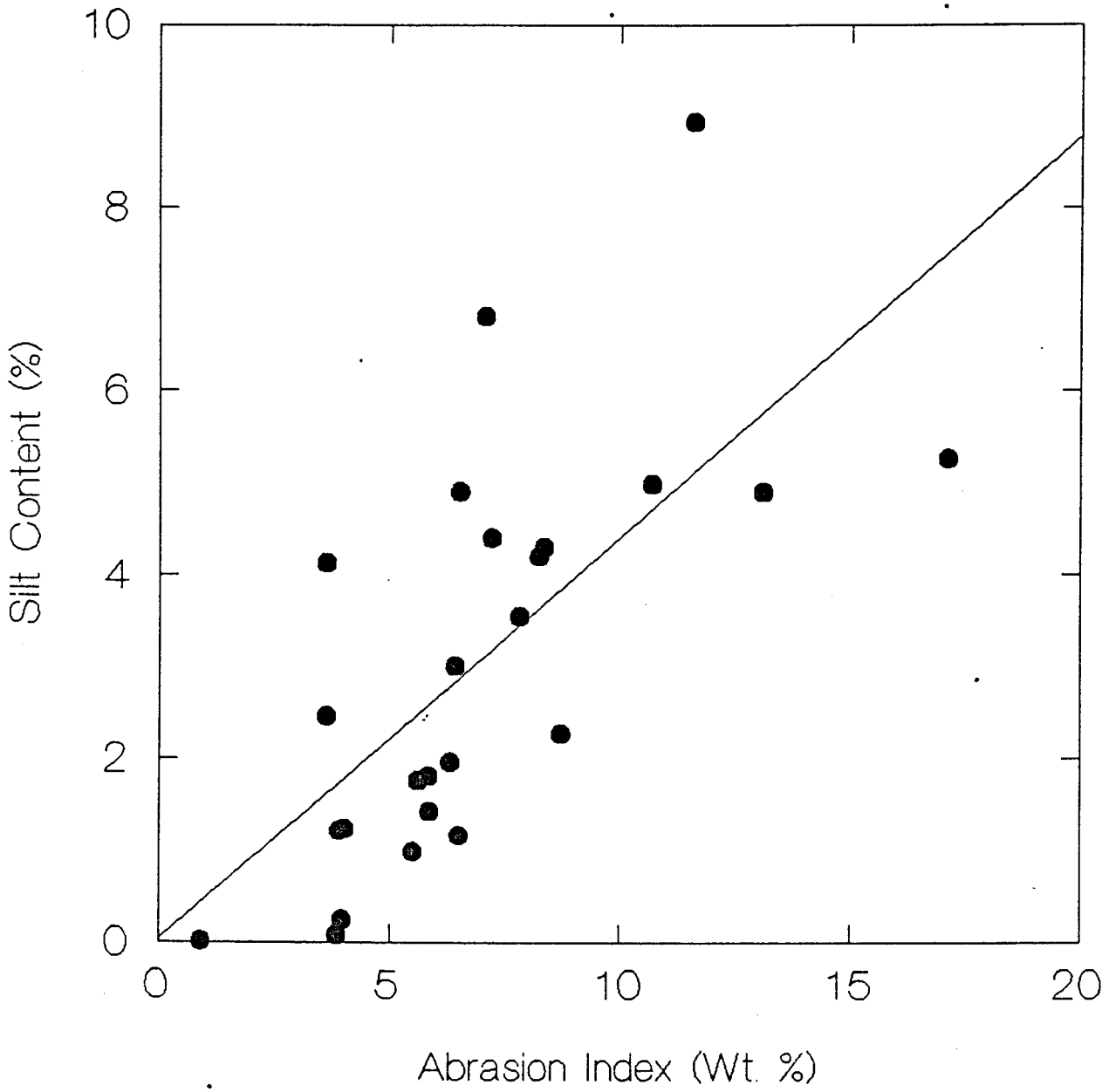


Figure 5-1. Scatterplot of silt content vs. LA abrasion loss.

The second point indicated by the correlations in Table 5-6 involves the apparent interrelationships between unit weight, void fraction, and the particle shape index. The correlations are highly significant in a statistical sense and, from a physical viewpoint, are internally consistent. For example, the negative correlations between unit weight (i.e., density in mass/volume) and void fraction (wt. %) imply that a unit volume of less dense material contains a high percentage of "air space," or alternatively, high density materials contain relatively little air. Similarly, the positive relationship between shape index and void fraction indicates that materials composed of particles that are more angular, necessarily exhibit a greater void fraction. Figure 5-2 presents an example scatterplot of the correlation between void fraction and particle shape index.

5.3.2 Multivariate Analyses

Principal component analysis (PCA), as used in this study, is based on the correlation matrix (Table 5-6). In essence, PCA serves to formally define the observations made above concerning the underlying patterns inherent in the correlation matrix. Specifically, the PCA results indicate that the variation in the eight key abrasive properties can be compactly expressed in terms of three composite variables. These composite variables may be described as follows:

1. Variable I—Particle size/shape including void fraction, unit weight, and particle shape.

2. Variable II—Degradability including silt content, abrasion loss, and wet aggregate durability.

3. Variable III—Silica/hardness including quartz content and Vickers hardness.

From an analytical perspective, the important result of the PCA is that the composite variables contain the physical information or "signal" exhibited in the raw material properties data. From a practical viewpoint, the composite variables (from PCA) form a convenient basis for determining whether the sample test materials, in fact, can be grouped into a relatively small number of distinct material "types."

To address the question of grouping materials into types, the multivariate statistical technique commonly referred to as cluster analysis was used. The results of this analysis suggest that based on experimentally determined physical properties, the test materials can be placed into five types (or clusters). Table 5-7 shows the breakdown of test materials into characteristic types.

In order to gain some appreciation for the differences between material types, average values were calculated for each type and for each of the material properties (i.e., abrasion through particle shape index). In turn, these average values are expressed as a percentage of the respective overall means (i.e., average values based on all 25 test materials). Figure 5-3 provides a graphical representation of these results.

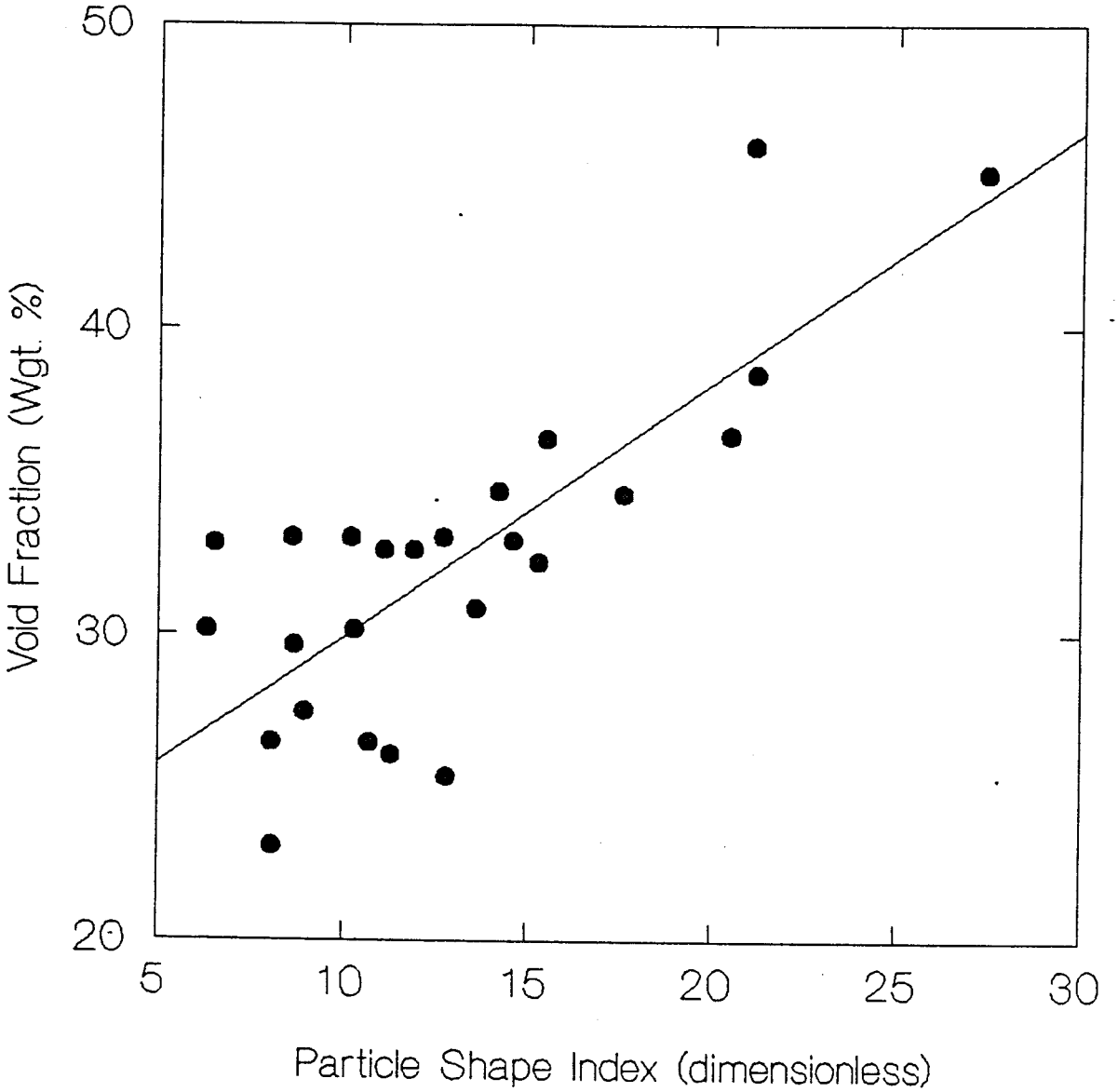


Figure 5-2. Scatterplot of percent void fraction vs. particle shape index.

TABLE 5-7. BREAKDOWN OF TEST MATERIALS BY CHARACTERISTIC TYPE

Type				
1	2	3	4	5
Presque Isle, ME—City Stockpile	Steamboat Springs, CO—Scoria	Sheridan, WY—Scoria	CO APCD—Washed Squeege	Kalispell, MT—"Old"
Sheridan, WY—Washed Sand	Boiler Bottom Ash	St. Xavier, MT	Steamboat Springs, CO—"Coarse" Sand	Missoula, MT—Pre-1987
Kalispell, MT—"New"			Washed Construction Sand	Thompson Falls—MT
Libby, MT—State Highway				Ronan, MT—City Sand
Libby, MT—City Sand				MDOT—Nine Pipes
Libby, MT—City Crushed Aggregate				Maine DOT Presque Isle
Columbia Falls, MT—"Old"				
Columbia Falls, MT—"New"				
Missoula, MT—1990				
Butte/Silver Bow, MT—Sand				
Steamboat Springs, CO—"Fine Sand"				
Steamboat Springs, CO—Squeege				

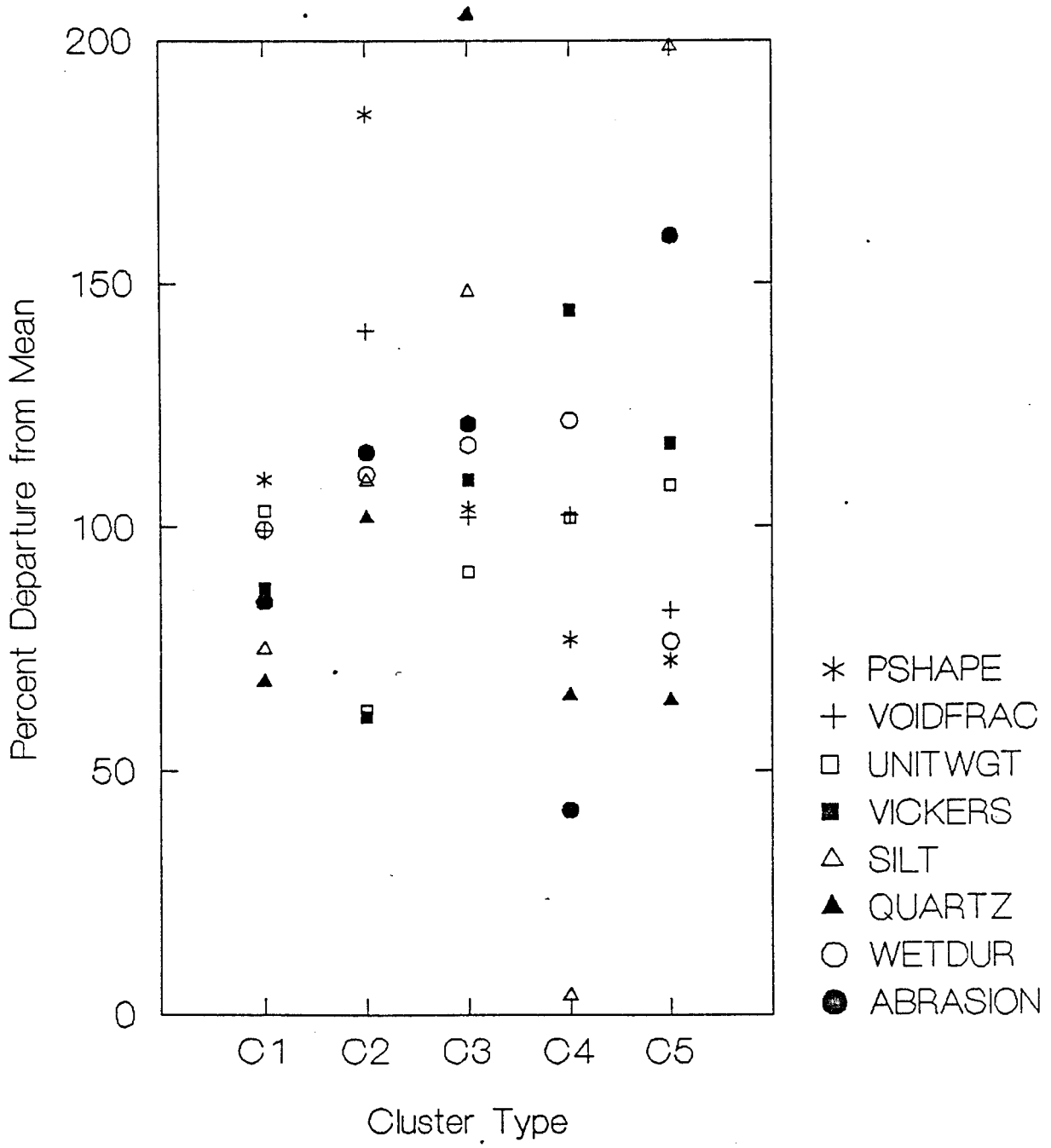


Figure 5-3. Percent deviation from mean value by cluster type.

Examination of Figure 5-3 suggests that the material types can be characterized as follows:

- C1—Materials exhibiting relatively low silt (0.99% to 4.9%) and quartz (10 to 36 mmol/L) contents; other material properties near the overall means (see Table 5-8).

- C2—Coarse and soft materials as indicated by high particle shape (21 to 27) and void fraction (45% to 46%) indices along with relatively low unit weight (860 to 1200 kg/m^3) and Vickers hardness values (340 to 460 kg/mm^2).

- C3—Materials that exhibit both high quartz (150 to 190 mmol/L) and high silt (4.1% to 4.9%) contents; other material properties near the overall means (see Table 5-8).

- C4—Relatively hard materials as indicated by low silt content (0.02% to 0.25%), low abrasion loss (0.90% to 4.0%), and high values for the Vickers hardness (550 to 1200 kg/mm^2) test.

- C5—Finely divided materials that are easily abraded; indicated by high silt content (4.3% to 8.9%) and high abrasion losses (7.1% to 17%).

Summary statistics for the entire experimental data set as tabulated by cluster type are shown in Table 5-8.

TABLE 5-8. SUMMARY STATISTICS—MATERIAL PROPERTIES BY CHARACTERISTIC CLUSTER TYPE

Parameter/type	LA abrasion loss (wt %)	Wet aggregate durability index	Quartz content (mmol/L)	Silt content (wt %)	Vickers hardness (kg/mm^2)	Unit weight (kg/m^3)	Void fraction (wt. %)	Particle shape index
Mean								
C1	5.85	75.5	26.6	2.29	572	1,723	32.2	13.3
C2	7.96	84.0	39.6	3.34	400	1,040	45.6	24.2
C3	8.36	88.5	171.6	4.52	718	1,516	33.2	13.6
C4	2.90	92.3	25.4	0.12	945	1,698	33.3	10.1
C5	11.0	58.0	25.0	6.06	766	1,809	27.0	9.53
E	6.89	75.7	38.8	3.05	654	1,666	32.5	13.1
Minimum								
C1	3.62	62.0	10.0	0.99	88.7	1,633	26.5	8.07
C2	7.21	68.0	39.4	2.28	343	856	45.1	21.1
C3	3.62	87.0	155.0	4.14	607	1,348	33.1	12.7
C4	0.90	85.0	15.9	0.02	554	1,627	30.2	6.3
C5	7.06	45.0	19.6	4.31	408	1,654	23.1	6.5
E	0.90	45.0	10.0	0.02	88.7	856	23.1	6.30
Maximum								
C1	8.24	94.0	36.5	4.91	1,163	1,916	38.5	21.2
C2	8.72	100.0	39.9	4.41	458	1,223	46.0	27.4
C3	13.1	90.0	187.6	4.90	828	1,683	33.2	14.6
C4	3.95	97.0	34.2	0.25	1,238	1,799	36.4	15.5
C5	17.1	73.0	29.1	8.93	1,052	1,863	33.0	12.8
E	17.1	100.0	187.6	8.93	1,238	1,916	46.0	27.4

SECTION 6

SIMULATED TRAFFIC TESTS

Two sets of experiments were performed in MRI's cold room. In the first set, selected antiskid materials were exposed to simulated traffic conditions on a wheel passage machine designed and constructed by MRI. In the other experiments, small scale tests were performed on common chemical deicers to determine the amount of solid material potentially available for resuspension. Both are described in detail below.

6.1 MATERIAL SELECTION

A total of seven abrasives and one deicer were evaluated on MRI's wheel passage machine. For the abrasives, at least one sample from each of the five material groups determined from the cluster analysis (Section 5.3) were tested as selected by the EPA work assignment manager (WAM). Table 6-1 lists the specific antiskid materials tested in the program.

For the seven abrasives listed in Table 6-1, a mixture of 90% abrasive and 10% NaCl (MO DOT road salt) was used for test purposes. This abrasive/deicer mixture reflects that typically used by local transportation agencies for ice and snow control as determined from the literature search and telephone survey.

With respect to the quantity of material applied during the wheel passage tests, six equivalent applications of 4,000 lb/lane mi were selected for all antiskid abrasives tested. This rate is indicative of the maximum application currently used by transportation agencies contacted in the telephone survey. The maximum application was used in the study to provide a sufficient amount of material on the track for adequate sample collection and analysis. In the case of the single deicer tested on the wheel passage machine, six applications of the AASHTO recommended rate of 500 lb/lane mi were used during simulated traffic testing.

In addition to the simulated traffic tests, three common chemical deicers were also evaluated in small scale experiments. The purpose of these experiments was to determine the amount of solid material potentially available for resuspension on paved roadways as well as to evaluate applicable sampling techniques for use in the simulated traffic tests. One equivalent application of 500 lb/lane mi, plus five reapplications of 250 lb/lane mi, was used for the deicers tested.

TABLE 6-1. ANTISKID MATERIALS EXPOSED TO SIMULATED TRAFFIC[a]

Test No.	Sample No.	Sample identification
1 & 1D[b]	1 & 1D	Holiday Sand and Gravel ice control sand[c]
2	2	Maine DOT Presque Isle stockpile[c]
3	3	Steamboat Springs scoria[d]
4	4	Columbia Falls new[d]
5	5	Colorado APCD washed squeege[d]
6	6	MO Department of Transportation (DOT) road salt[c]
7	8	Steamboat Springs coarse sand[d]
8	9	Sheridan, WY scoria[d]

[a] All abrasives combined with NaCl in a 90:10 mixture.

[b] Test No. 1 was performed with ice on the test track as was the case in the other tests. Test 1D was performed dry without ice on the track.

[c] See Table 5-3 for material properties.

[d] See Table 5-4 for material properties.

The deicers evaluated in the small scale tests were MO DOT road salt; CMA; and Peladow® (a commercial CaCl compound). The properties of Peladow® are as follows:

- Manufacturer: Dow Chemical USA
- Lot Number: ML861006
- Assay: 91.0% $CaCl_2$ (ASTM E 449); 2.16% KCl; 1.7% NaCl; and 0.03% $MgCl_2$

6.2 TRAFFIC TESTS

A total of eight simulated traffic tests were performed in MRI's cold room. The following describes the test apparatus, protocol, and results obtained in the experimental program.

6.2.1 Description of Test Apparatus

The MRI wheel passage machine, shown in Figure 6-1, was designed and built to duplicate the forces exerted on road surfaces by a conventionally loaded tire. The

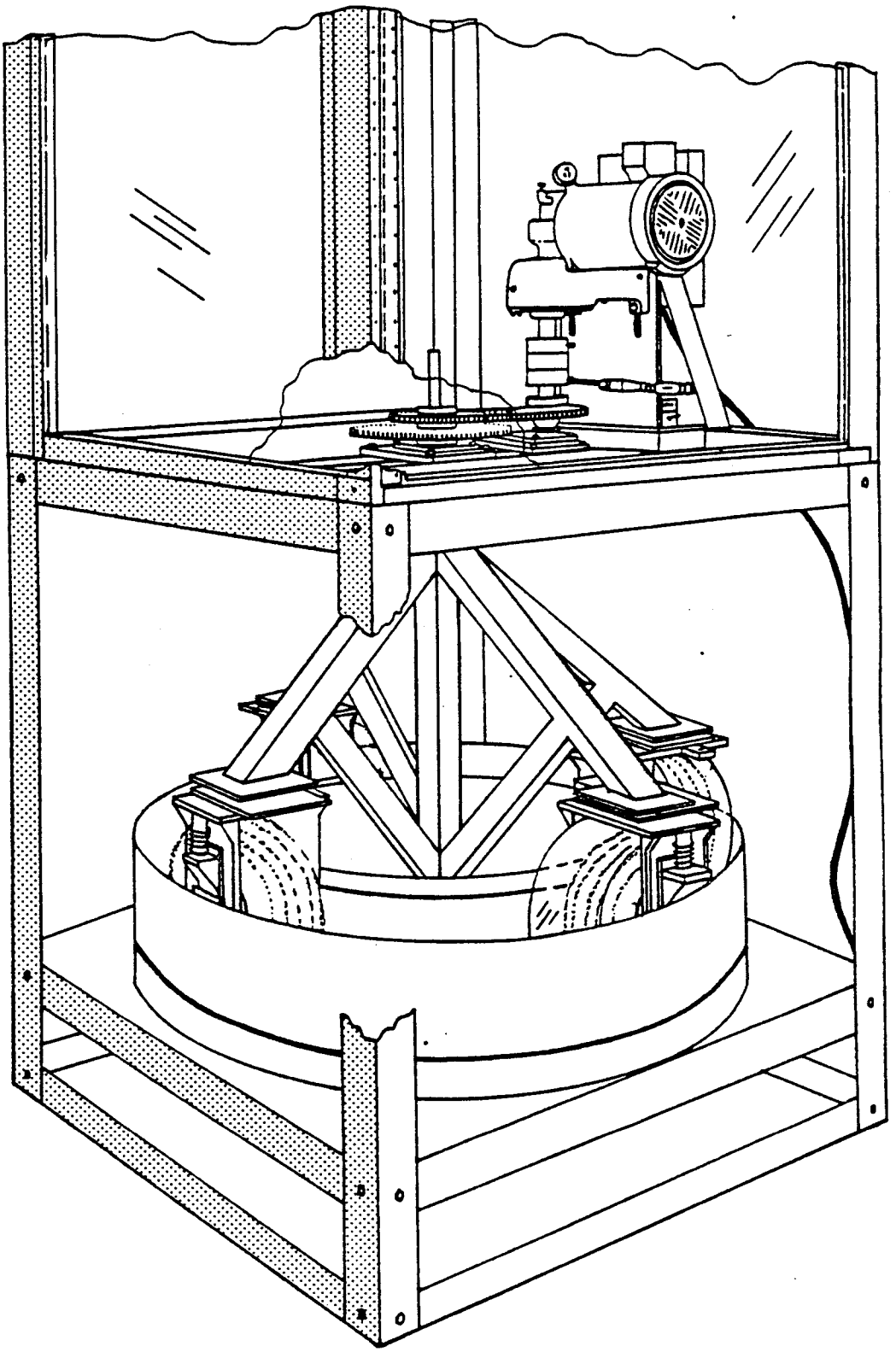


Figure 6-1. MRI wheel passage machine.

machine was a modified design of the standard circular track polishing machine (ASTM E660) used in pavement surface wear research.

The wheel passage machine was designed with four wheel assemblies attached to a central frame. The central frame is chain-driven by a gear reduction/motor unit. The final rotational speed is accomplished with the use of different-sized sprockets. Identical gears are used on the driver and the driven to obtain the required 32 rpm. A 8:1 ratio in gear size is used to obtain the 4 rpm required in the first stage of the test.

The desired normal load is induced by two 375 lb/in compression springs located on each wheel assembly. The springs were adjusted to deliver a footprint pressure of 28 to 30 psi on the track surface. Each wheel assembly pivots somewhat reducing the amount of side abrasion at the tire-track interface caused by the small turning radius of the machine. To obtain full track coverage by the tires, two of the four wheels were offset from one another.

For the purpose of these particular tests, the track of the wheel passage machine was reconstructed using a 2-in thick layer of Type 1 Portland cement concrete having a 50/50 coarse/fine sand mixture. The aggregate used in the mix design had a maximum size of 3/8 in limestone with a rated slump of 2.5 ± 1 in and a compressive strength greater than 4000 psi. The concrete was non air-entrained and had a density of 145 lb/ft^3. The concrete track was cured for many months before testing.

The concrete track was sandblasted and epoxied to the base plate of the machine. Masonite shielding was installed around the inside and outside diameters of the track and extended high enough to contain debris from leaving the track area. Interior curbing was built using a conventional sand cement mixture. The curbing forced particulate to drop back into the tracks of the tires.

After Test No. 6 the track was reconditioned by again sandblasting the surface and laying a new, thin coat of the same sand—Portland cement mix as above onto the cleaned track. The cure time was about 30 days. This technique proved to be unsatisfactory because of the friability of the top layer on the track. This friability caused substantial problems during Test Nos. 7 and 8 as discussed below.

6.2.2 Test Protocol

6.2.2.1 Pretest Preparations--

Prior to each test, the track surface was cleaned with a wire brush followed by water and ethyl alcohol rinses. The surface was then visually inspected to assure that all tire debris and other loose material had been removed. If required, the brushing/rinsing procedure was repeated to obtain a clean track surface free of residue.

After cleaning the test track, the cold room temperature was decreased to 15°F overnight. Approximately 2 L of chilled water was then added to the track surface and

allowed to freeze overnight. This produced a layer of ice approximately 0.125 in thick suitable for testing. The cold room temperature was then raised to 25°F and the equipment allowed to equilibrate prior to testing.

Finally, to complete pretest preparations, the abrasive and/or deicer sample to be evaluated was split from the bulk material using a riffle, placed in the cold room, and equilibrated to a temperature of 25°F. Six equal quantities of test material were then weighed into aluminum containers and the data recorded appropriately. The remaining bulk material (after splitting out the track sample) was analyzed for silt content using the method outlined previously in Table 3-5, which is reproduced here as Table 6-2 (Cowherd et al., 1988).

6.2.2.2 Test Procedure--

To begin the test, the contents of one sample container were applied to the track surface by broadcasting. The wheel passage machine was then started and the center shaft rotated at 4 rpm for a period of 1 h. During this period, the ice layer started to become "slushy" and/or "muddy" with some free brine present.

At the end of the first hour, the material was manually redistributed (by scraping) into the center of the track and the contents of the second container applied to the surface. The machine was then restarted for another one hour period with the material again being redistributed at the end of the period. This procedure was repeated four additional times until all six samples had been applied to the test track.

After the final application of antiskid material (i.e., after 6 h of run time), the machine was allowed to operate continuously until an equivalent of 5,000 cumulative vehicle passes was reached. During this period, the material was redistributed into the center of the track at approximately 60-min intervals. At the end of 5,000 passes, the machine was stopped and heat lamps applied overnight to melt any remaining ice and evaporate the standing water. The cold room temperature was also adjusted to 35°F for the remainder of the test. The drying procedure produced a visually dry but "pasty" material on the track surface with a high surface moisture content (see Section 6.2.4 below).

After completion of the first 5,000 passes, a small grab sample was collected from the track for moisture analysis. (Note that silt analysis of this small sample was not feasible.) The machine was also reconfigured to rotate the center shaft at 32 rpm for the remainder of the test duration.

After the first track sample was collected at 5,000 passes, the machine was restarted and allowed to run for an additional 10,000 vehicle passes. During this period, the apparatus was stopped approximately every half hour and the material redistributed into the center of the track by gentle brushing. The machine then operated in 10,000 pass increments until a maximum of 65,000 equivalent vehicle passes was reached and the test terminated.

TABLE 6-2. SILT ANALYSIS PROCEDURES

1. Select the appropriate 8-in diameter, 2-in deep sieve sizes. Recommended U.S. Standard Series sizes are 3/8 in, No. 4, No. 20, No. 40, No. 100, No. 140, No. 200, and a pan. Comparable Tyler Series sizes can also be utilized. The No. 20 and the No. 200 are mandatory. The others can be varied if the recommended sieves are not available or if buildup on one particular sieve during sieving indicates that an intermediate sieve should be inserted.

2. Obtain a mechanical sieving device such as vibratory shaker or a Roto-Tap.

3. Clean the sieves with compressed air and/or a soft brush. Material lodged in the sieve openings or adhering to the sides of the sieve should be removed (if possible) without handling the screen roughly.

4. Obtain a scale (capacity of at least 1,600 g) and record make, capacity, smallest division, date of last calibration, and accuracy (if available).

5. Tare sieves and pan. Check the zero before every weighing. Record weights.

6. After nesting the sieves in decreasing order with pan at the bottom, dump dried laboratory sample (probably immediately after moisture analysis) into the top sieve. Brush fine material adhering to the sides of the container into the top sieve and cover the top sieve with a special lid normally purchased with the pan.

7. Place nested sieves into the mechanical device and sieve for 20 min. Remove the pan containing the minus No. 200 material and weigh. Replace pan beneath the sieves and sieve for another 10 min. Remove pan and weigh. When the differences between two successive pan sample weighings (where the tare of the pan has been subtracted) is less than 3.0%, the sieving is complete.

8. Weigh each sieve and its contents and record the weight. Check the zero before every weighing.

9. Collect the laboratory sample and place the sample in a separate container if further analysis is expected.

At the end of each 10,000 pass increment, two material samples were collected from different portions of the test track by a combination of hand sweeping and vacuuming. Two equal areas of the track surface were sampled in a manner similar to that used in traditional paved road studies (Cowherd et al., 1988). In this case, however, a small brush and pan followed by a small, battery powered vacuum (Mini Vac® equipped with a 37-mm filter cassette and Millipore Type AA filter) was used for sample collection. The two samples were analyzed separately for moisture content and then combined for silt analysis. (Note that due to the small sample size, the standard moisture and silt analysis methods were modified as described later in this report.)

Finally, at the completion of each test, all material remaining on the track surface was vacuumed into tared bags and analyzed for silt content. In this case, however, a larger hand-held vacuum (Dirt Devil®) was used for sample collection. Standard analysis procedures were used for the determination of silt content as shown previously in Table 6-2.

6.2.3 Analytical Methods

To meet the unique analytical requirements of the program, several special methods were used to analyze the samples collected from the test track. The following outlines the modified analytical methods used during the simulated traffic tests.

6.2.3.1 Analysis of Abrasives--

At 15,000 passes, and every 10,000 passes thereafter, the two small samples collected from the test track were analyzed for moisture and silt content using modified versions of the standard analytical methods for these parameters. In the case of moisture content, the standard MRI technique (Table 6-3) was followed except that the drying time was limited to 1 h. This was deemed appropriate due to the small size of the samples collected and the substantial amount of organic tire debris (e.g., carbon black) visibly present in the samples.

For determination of silt content, the abrasive material was hand sieved by brushing through a 200 mesh screen. Brushing of the sample was found necessary since the small particles contained in the samples tended to agglomerate and blind the larger screens when a full sieve stack was attempted. Otherwise, the same weighing and data recording procedure outlined in Table 6-2 was used.

6.2.3.2 Deicer Analyses--

For road salt, the samples collected from the test track were extremely small (i.e., a few tenths of a gram) and appeared to contain substantial quantities of tire wear particles. Therefore, special methods were used to evaluate both the particle size distribution and chemical (i.e., NaCl) content of the samples collected.

Each sample was sonically sieved using the general technique outlined in Table 6-4 (Kinsey and Coveney, 1986). In this case, however, no mechanical sieving was

TABLE 6-3. MOISTURE ANALYSIS PROCEDURE

1. Preheat the oven to approximately 110°C (230°F). Record oven temperature.

2. Tare the laboratory sample containers which will be placed in the oven. Tare the containers with the lids on if they have lids. Record the tare weight(s). Check zero before weighing.

3. Record the make, capacity, smallest division, and accuracy of the scale.

4. Weigh the laboratory sample in the container(s). Record the combined weight(s). Check zero before weighing.

5. Place sample in oven and dry overnight.[a]

6. Remove sample container from oven and (a) weigh immediately if uncovered, being careful of the hot container; or (b) place tight-fitting lid on the container and let cool before weighing. Record the combined sample and container weight(s). Check zero before weighing.

7. Calculate the moisture as the initial weight of the sample and container minus the oven-dried weight of the sample and container divided by the initial weight of the sample alone. Record the value.

8. Calculate the sample weight to be used in the silt analysis as the oven-dried weight of the sample and container minus the weight of the container. Record the value.

[a] Dry materials composed of hydrated minerals or organic materials like coal and certain soils for only 1½ h. Because of this short drying time, material dried for only 1½ h must not be more than 2.5 cm (1 in) deep in the container.

TABLE 6-4. SONIC SIEVING PROCEDURE

1. Obtain a sonic sieving apparatus.

2. Select the appropriate sieves that are optionally available for use with the above machine. The sieves commonly utilized are the 53-μm, 20-μm, and 10-μm sieves.

3. Obtain an analytical balance with the smallest division being 0.01 mg.

4. The material to be sieved on this machine is bottom pan (< 75 μm) catch from the mechanical silt analysis procedure (Table 2-8).

5. Clean the sieves in a low wattage (< 800 watts) ultrasonic bath, taking care to immerse the sieves edgewise only in the solvent. The use of Freon T.F. as a solvent is recommended because of its fast drying time. Once the sieves are clean, handle them only with cloth gloves to prevent contamination and static charge buildup. Latex gloves are not recommended.

6. Tare weigh the sieves and the catch pan. Weigh each sieve and the catch pan three times, alternating sieves between each weighing, and record each weight. Calibrate the balance with Class S weights prior to each weigh period, and periodically check the balance during its use.

7. After nesting the sieves in decreasing order of size, place the sample into the top sieve. The sample should weigh between 0.5 and 1.0 g. The sample weigh boat must be tare weighed prior to receiving the sample and again after the sample is introduced to the top sieve. The difference is subtracted from the sample weight and is recorded as material lost due to handling. Due to the hygroscopic nature of oven-dried soils, the sample will gain moisture. Thus the work must be done quickly without stopping for any length of time during the entire test cycle.

8. Once the material is placed on the top sieve, cover the top sieve with the sound wave generating diaphragm and place the sieves in the sonic shaker. The total sieving time is 5.0 min. With the sonic shaker in the sieve mode and the amplitude set on 2, sieve the material. Increase the amplitude to 5 after 1 min. After 1.5 min (elapsed time), switch the machine to the sift/pulse mode until the end of the test. If during the sift/pulse mode appreciable amounts of material collect on the sieve wall, carefully tap the sides where the particulate is adhering using a wooden stick.

9. After the 5-min sieving, remove the sieves and promptly weigh each sieve as rapidly as possible. Repeat the weighing two more times. Record each weight and do not interrupt this procedure.

10. Calculate the average tare and final weights of each sieve and pan. Subtract the tare from the final weight to find the average amount retained on each sieve and pan. Calculate both the mass and the percentage retained. Record these values on the data sheet.

performed to remove larger particles prior to sonic sieving. Instead, a 75-μm (200 mesh) screen was used as the top size which was followed by a 53- and 20-μm screen and associated pan. Also, the entire sample was analyzed instead of the amounts specified in Step 7 of Table 6-4.

Since samples appeared to contain tire debris, a chemical analysis was performed to determine the NaCl content of each deicer sample. This analysis was performed by an aqueous extraction of the entire sample (recombined after sonic sieving) followed by an analysis for Na^+ and Cl^-. The analytical results showed that the water soluble fraction of each sample (total dissolved solids) was composed of almost 100% NaCl with a small amount of other undefined material (assumed to be either track or tire debris).

6.2.4 Test Results

6.2.4.1 Abrasive Test Results--

The moisture and silt data for the seven antiskid abrasives tested are shown in Figures 6-2 to 6-7. In these figures, data for the original bulk material along with that for the 6 small track samples are plotted against equivalent vehicle passes. The individual data points have also been connected to produce an overall "degradation curve" for each test.

As shown by the above figures, both moisture and silt content vary substantially as a function of vehicle passes. For example, the moisture content of the material rises rapidly at first, dries due to wheel friction, and stabilizes at about 25,000 passes.

In the case of silt content, the results would indicate a rapid increase in fines generation until around 35,000 passes, at which point silt content tends to level off. Thus, if additional testing was to be performed, the test could be terminated at 35,000 passes without adversely affecting data quality. In addition, the silt data also show that Sample 1 (from data cluster 4—see Section 5.3) exhibits the lowest overall increase in fines as compared to Sample 2 (from cluster 5) which exhibits the highest increase. The significance of these results is discussed later in this report.

It should also be noted that two different traffic tests were performed on the one of the antiskid abrasives (i.e., Holiday Sand and Gravel ice control sand) shown in Figures 6-2 and 6-5. Sample I was ice control sand tested using the method described above whereas Sample 1D indicates the same material evaluated without ice on the track.

As shown by the silt data in Figure 6-5, the amount of fine material in Sample 1 is higher than Sample 1D at traffic levels above about 15,000 passes. These results might suggest that abrasive wear during exposure to the ice melting process could be more pronounced as compared to the "no-ice" case.

A mass balance was also prepared for each abrasive tested using the experimental data. In this determination, the original amount of material applied to the track was

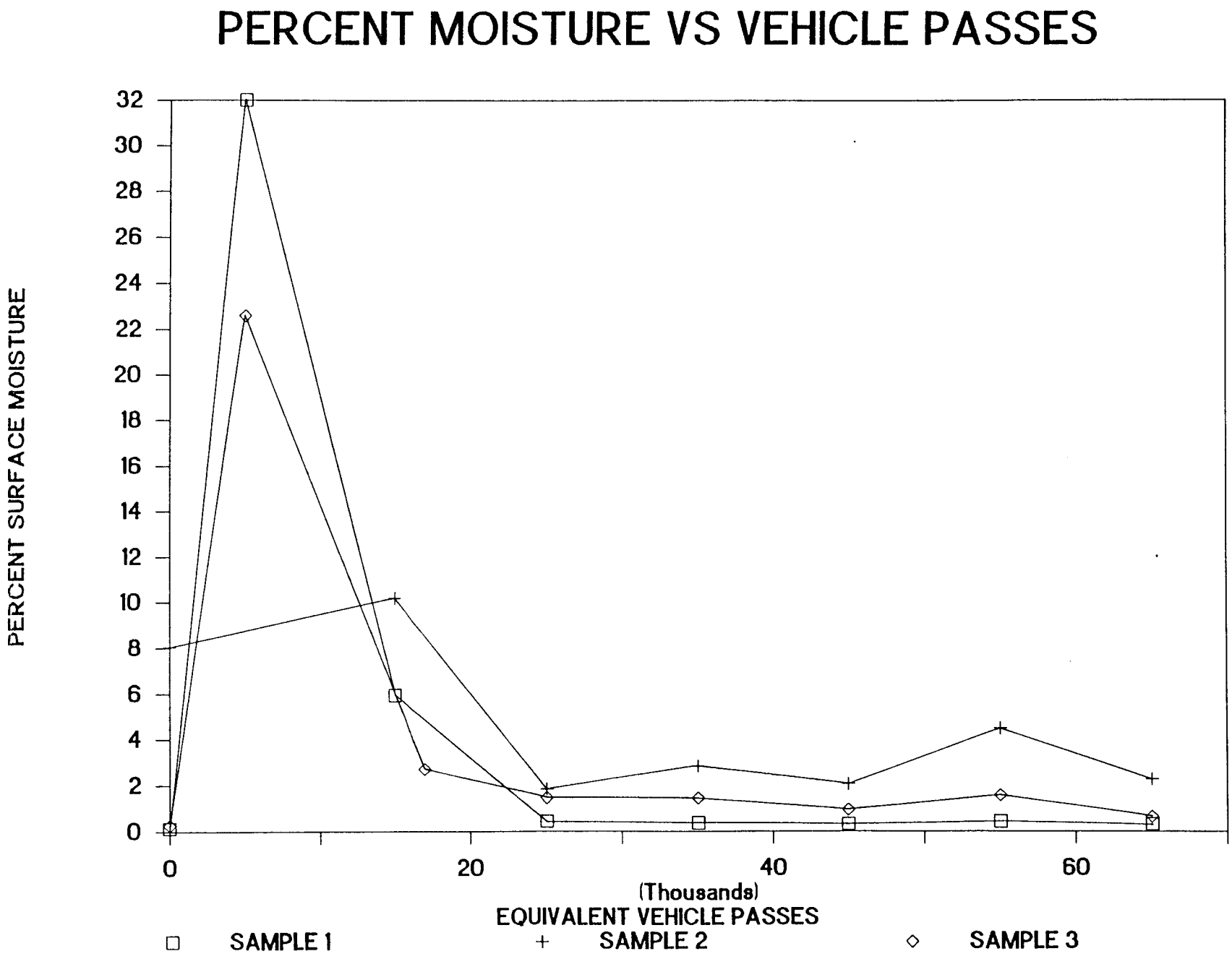


Figure 6-2. Percent moisture vs. equivalent vehicle passes for Samples 1-3. (See Table 6-1 for sample identification.)

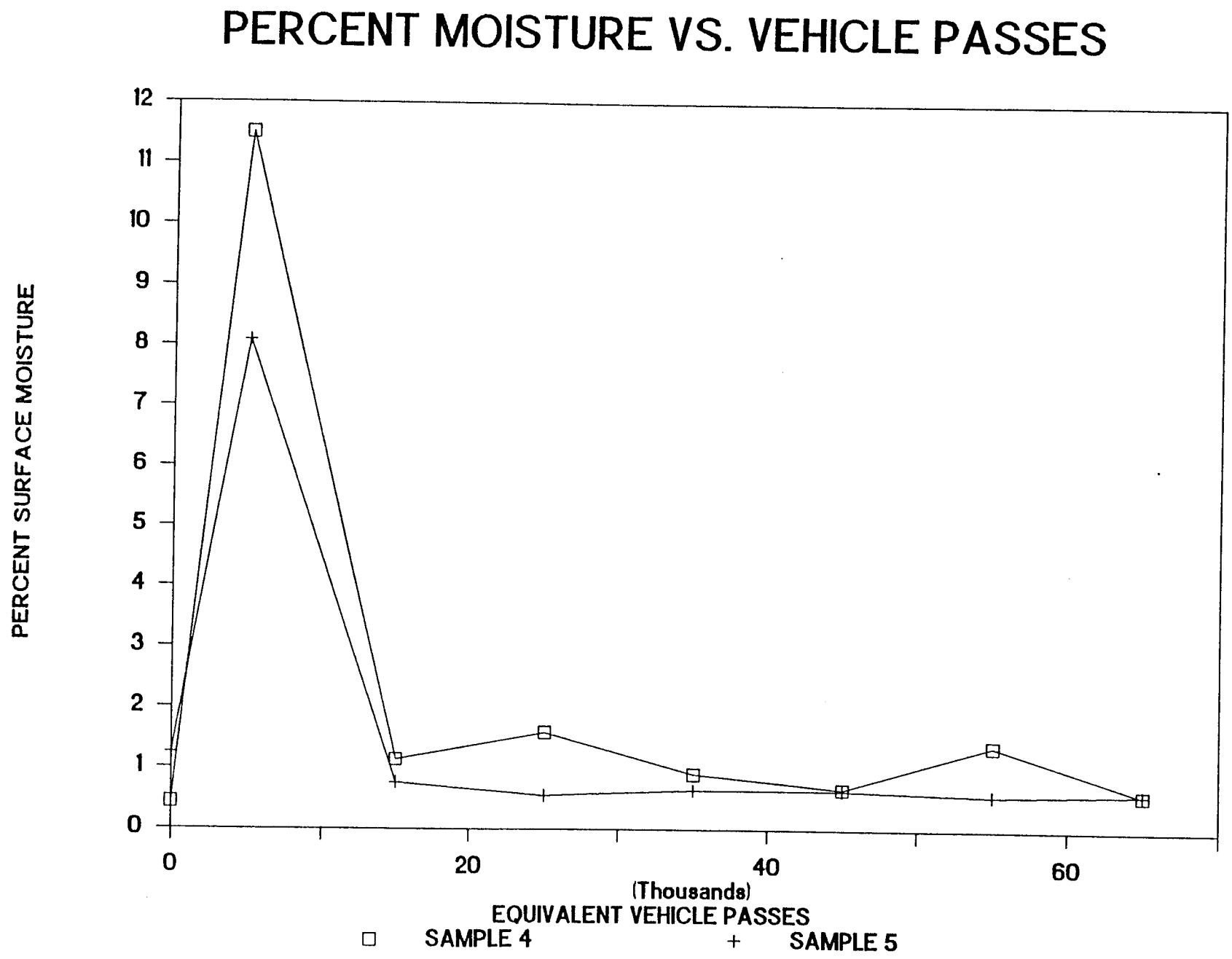


Figure 6-3. Percent moisture vs. equivalent vehicle passes for Samples 4 and 5. (See Table 6-1 for sample identification.)

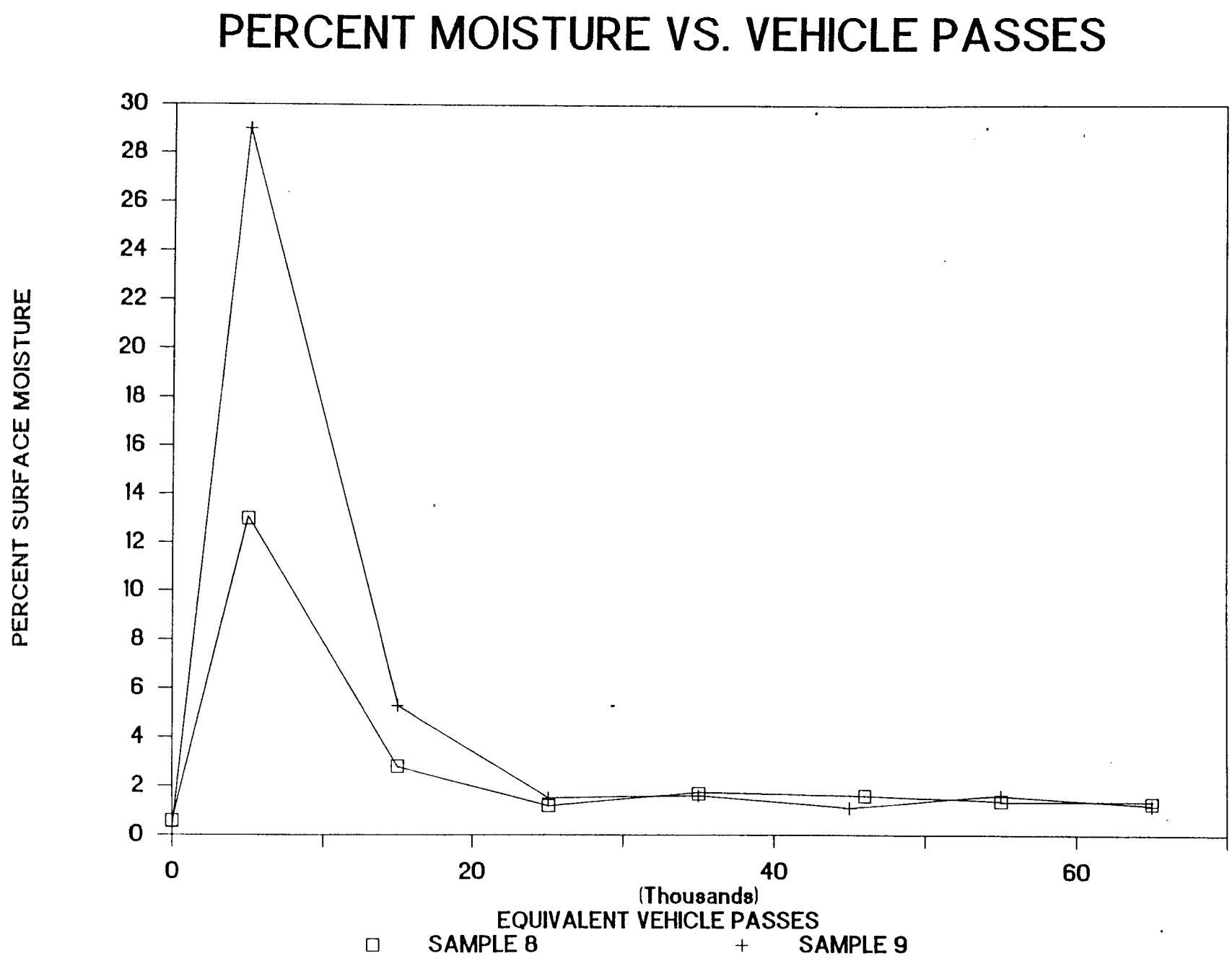


Figure 6-4. Percent moisture vs. equivalent vehicle passes for Samples 8 and 9. (See Table 6-1 for sample identification.)

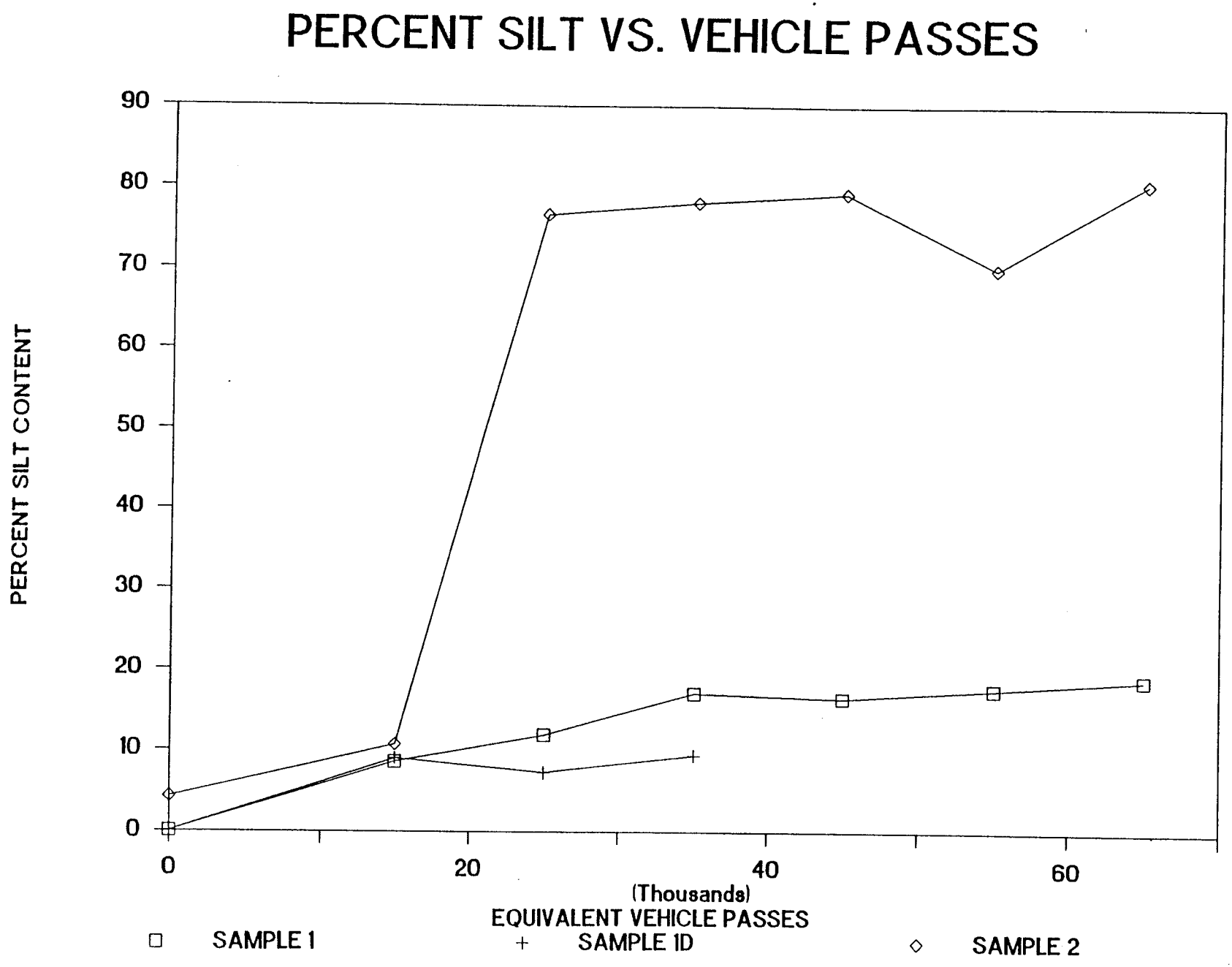


Figure 6-5. Percent silt (% < 75 μmP) content vs. equivalent vehicle passes for Samples 1, 1D, and 2. (See Table 6-1 for sample identification.)

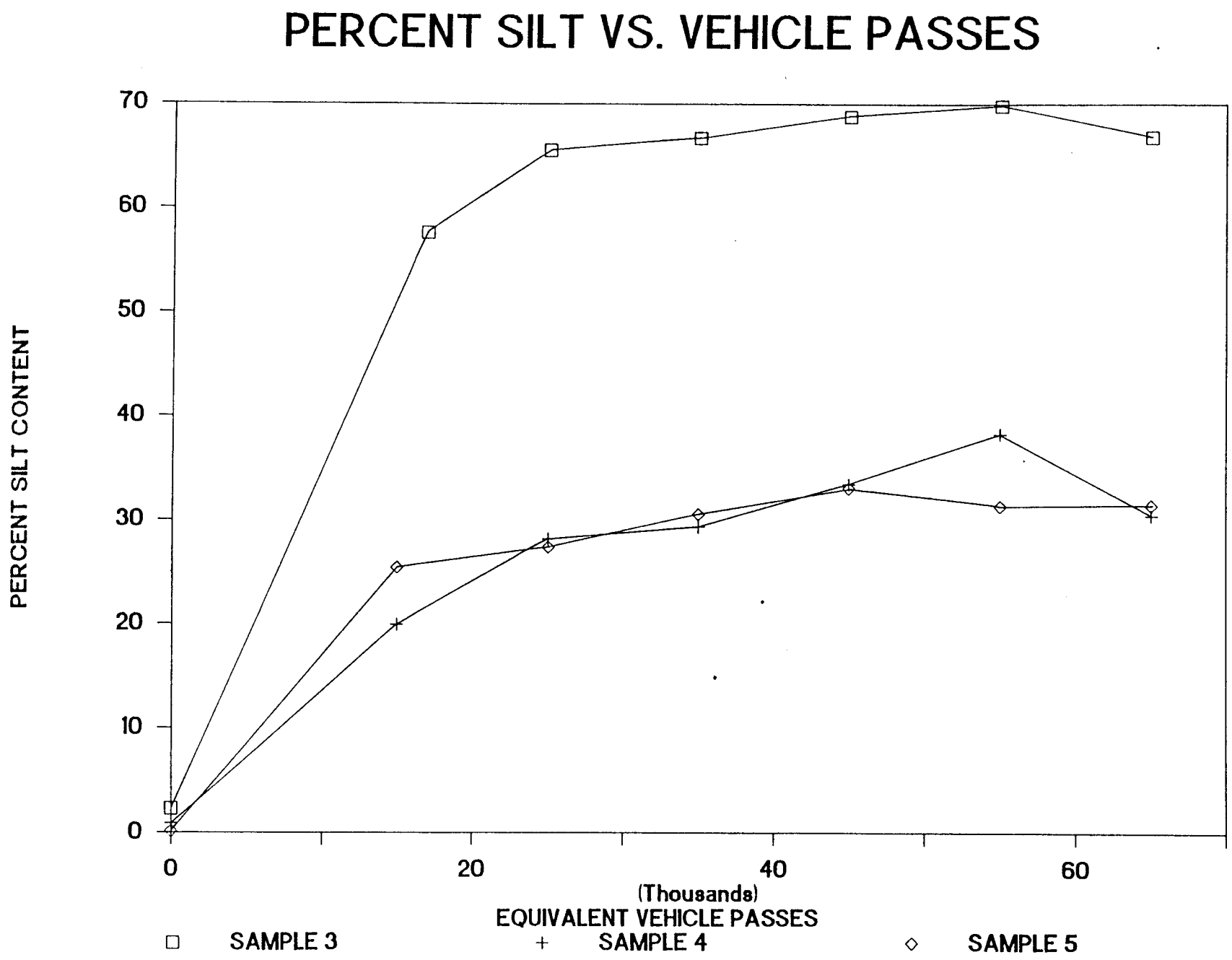


Figure 6-6. Percent silt (% < 75 μmP) content vs. equivalent vehicle passes for Samples 3, 4, and 5. (See Table 6-1 for sample identification.)

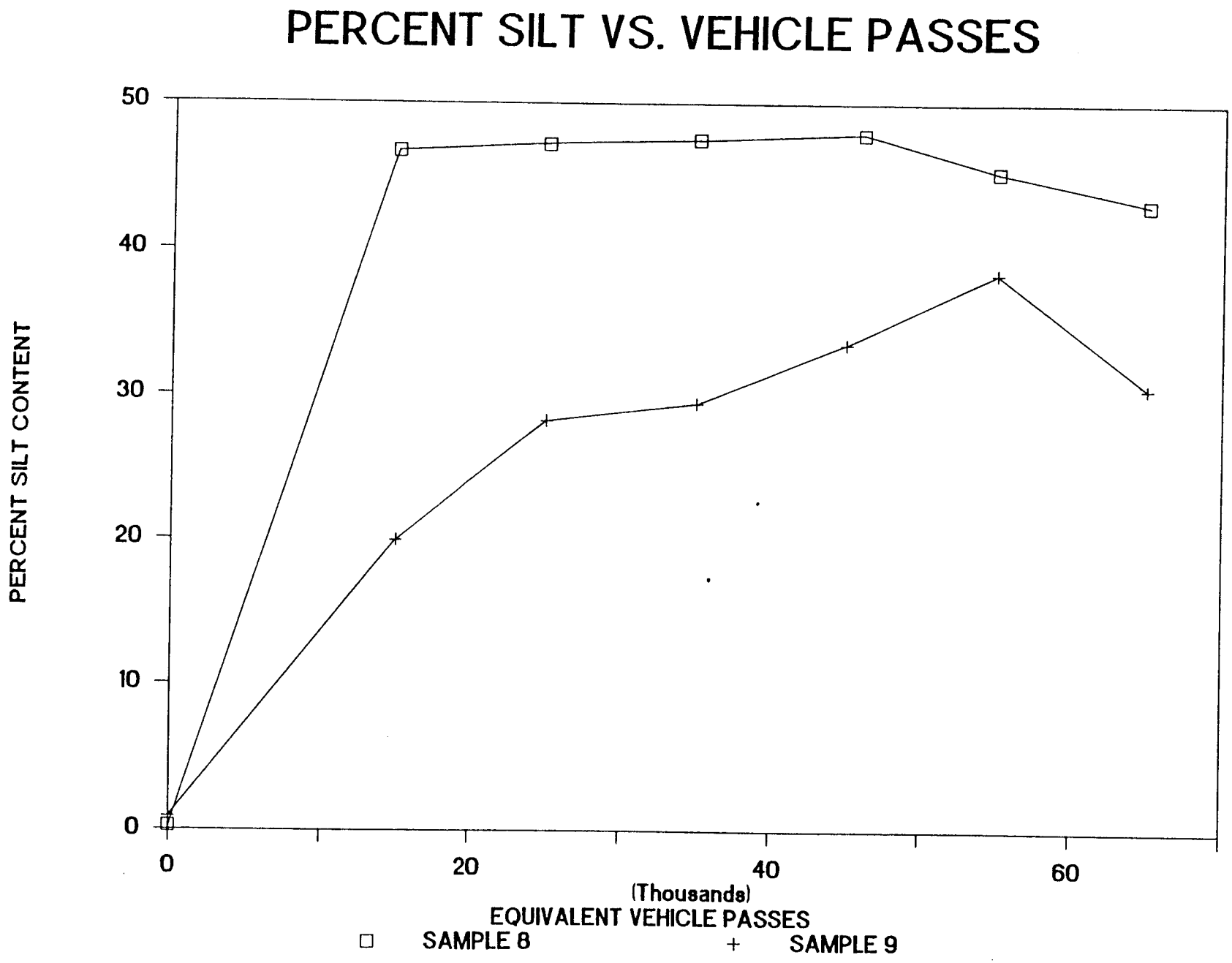


Figure 6-7. Percent silt (% < 75 μmP) content vs. equivalent vehicle passes for Samples 8 and 9. (See Table 6-1 for sample identification.)

compared to that recovered by sampling both during and after testing. The results of the mass balances performed are shown in Table 6-5.

As shown in Table 6-5, a certain portion of the original sample mass was lost to the cold room environment for all abrasives tested except for Samples 8 and 9 (Test Nos. 7 and 8). In these tests, more material was recovered from the track than was originally applied. This apparent increase in sample mass was probably due to the production of paving wear debris during testing. (Note that increased paving wear was presumably caused by resurfacing of the test track prior to Test No. 7—see Section 6.2.1 above.) Since the contribution of track wear to the overall silt content cannot be distinguished from that of the abrasive itself, the results of these two experiments are obviously invalid and thus were not used in the data analysis.

6.2.4.2 Deicer Test Results--

The particle size data for Test No. 6 of rock salt are shown in Table 6-6 as a function of vehicle passes. These data represent the particle size distribution of the entire sample collected from the test track as determined by sonic sieving.

After sonic sieving, each track sample was recombined and chemically analyzed for total dissolved solids, Na^+, and Cl^- content. The results of these analyses are shown in Table 6-7. Also shown in Table 6-7 is the percent NaCl in each sample as calculated from the analytical data. As seen from these results, only a relatively small portion (i.e., approximately 30% or less) of each sample was composed of NaCl with the remainder consisting of insoluble material (e.g., tire and/or track debris).

6.3 SMALL SCALE EXPERIMENTS

As an adjunct to the simulated traffic tests, small scale experiments were also conducted in MRI's cold room to: (1) investigate suitable sampling methods for use in the simulated traffic tests; and (2) determine the amount of solid material potentially available for resuspension resulting from the application of common deicers. The following describes the apparatus, protocol, and results associated with the small scale experiments.

6.3.1 Description of Apparatus

The test apparatus used in the small scale experiments consisted of a series of 6 x 12 x 3 in solid blocks constructed of Portland cement concrete. Each block contained a depressed area (or "well") having approximate internal dimensions of 4.5 in wide x 10.5 in long x 0.75 in deep. The well provided an area of 0.328 ft^2 for the growth of ice. Up to three blocks were used during each test.

In addition to the blocks, heat lamps were also used to melt any remaining ice and evaporate the water. A modified ink roller was also provided to crush and distribute the deicer particles over the internal block surface and to simulate vehicles moving over a

TABLE 6-5. TEST TRACK MATERIAL BALANCE

Test No.	Sample No.	Material identification	Total material applied to test track (g)[a]	Total material recovered from test track (g)	Material losses[b]	
					g	Percent
1	1	Holiday Sand & Gravel ice control sand	816	521.5	294.5	36.1
1D	1	Holiday Sand & Gravel ice control sand	816	716.2	99.8	12.2
2	2	Maine DOT sand—Presque Isle	816	471.3	344.7	42.2
3	3	Steamboat Springs scoria	816	613.6	202.4	24.8
4	4	Columbia Falls—new	816	707.5	108.5	13.3
5	5	Colorado APCD washed squeege	816	717.1	98.9	12.1
6	6	MO DOT road salt	102	23.7	78.3	76.8
7	8	Steamboat Springs coarse sand	774[c]	1214.7	<440.7>	<157>
8	9	Sheridan, Wyoming, scoria	774[c]	989.6	<215.6>	<128>

[a] Equivalent to 6 applications of a 90:10 mixture of abrasive and rock salt (NaCl) at 4,000 lb/lane mi each or 1 application of rock salt (NaCl) at 500 lb/lane mi + 5 applications of 250 lb/lane mi each.

[b] Losses to cold room environment regardless of fate; < > indicate gain in material mass.

[c] After rebuilding of test track and slight change in track area.

TABLE 6-6. PARTICLE SIZE DATA FOR TRAFFIC TEST NO. 6 (ROCK SALT)

Equivalent vehicle passes	Sample weight (g)[a]	Weight percent < stated size[b]		
		< 75 μmP	< 53 μmP	< 20 μmP
15,000	0.4123	51.1	37.7	4.36
25,000	0.3915	47.6	33.5	0.778
35,000	0.1865	49.8	35.3	1.63
45,000	0.2033	42.1	28.6	1.33
55,000	0.2854	44.4	30.2	2.28
65,000	0.3771	44.2	26.9	1.98
Post-test	21.8[b]	48.2	NA[b]	NA[a]

[a] Total mass recovered from test track.

[b] NA = not available.

TABLE 6-7. RESULTS OF CHEMICAL ANALYSES FOR NaCl TESTS

Sample identification	Total dissolved solids (wt %)[a]	Na^+ content (wt %)[b]	Cl^- content (wt %)[b]	Overall NaCl content in sample[c]
15,000 passes	30.0	55.6	34.4	27.0
25,000 passes	25.3	57.4	35.9	23.6
35,000 passes	48.0	29.2	16.8	22.1
45,000 passes	26.3	58.2	32.9	24.0
55,000 passes	28.6	59.3	35.9	27.3
65,000 passes	34.1	56.9	35.5	31.6
Post-test sweepings	39.6	58.8	16.5	29.8

[a] Percent water-soluble fraction in as-received sample.

[b] Percent Na^+ and Cl^- in water-soluble fraction of sample.

[c] Values calculated from data in other columns.

paved road. Finally, large plastic syringes fitted with large bore needles were used to remove wash water from the test blocks.

6.3.2 Test Protocol

In **preparation for testing**, a layer of ice was grown in the well of the test blocks. This was accomplished by first cleaning each block and placing it in a freezer compartment overnight. A container of deionized water was also chilled in a refrigerator set at 40°F. After equilibration, 100 cm^3 of the chilled water was added to each block and allowed to freeze overnight. Also during this period, the 37-mm, Millipore Type AA filters for the Mini Vac® were equilibrated at constant temperature and humidity (i.e., 23° ± 1°C and 45% ± 5% relative humidity) and tare weighed in preparation for testing.

To **conduct each test**, the blocks were removed from the freezer, placed in the cold room, and equilibrated to a temperature of 35°F. Next, 4.11 g of deicer was distributed evenly across the surface of each block. (Note that this amount of deicer is equivalent to an initial application of 500 lb/lane mi plus five reapplications of 250 lb/lane mi per AASHTO recommendations for application of deicing salts.) The modified ink roller was then used to crush the deicer particles and spread the deicer/brine mixture equally across the test surface. Any deicer/brine remaining on the roller was washed onto the block with deionized water. The block was dried by heat lamps overnight.

Dry residue on the blocks was quantified by dry surface sampling followed by wet flushing. Dry sampling was used to estimate the amount and size of fine material potentially available for resuspension. Wet flushing was conducted to determine the amount of deicer potentially removed by post-storm runoff.

For **dry sample recovery**, a coarse brush was used to loosen the particles adhering to the block surface. The solid material was then removed by a combination of brushing and dry vacuuming using the Mini Vac® described previously. The quantity and particle size distribution of the samples collected were determined by gravimetric analysis followed by sonic sieving of the entire sample (see Section 6.2.3 above).

After removal of the dry residue from the test blocks, a series of three **hot water washes** were performed. This was accomplished by first heating a 1-L beaker of deionized water to a boil. The water was allowed to cool slightly and transferred to a plastic squirt bottle. Each block was then flushed with approximately 360 cm^3 of hot water. Brine was removed from the block by a large hypodermic syringe and quantitatively transferred to tared glass beakers. The beakers were dried in a laboratory oven (110°C or 230°F) overnight, cooled in a desiccator, and the residue determined by gravimetric analysis.

6.3.3 Test Results

The results of the small scale experiments are shown in Tables 6-8 and 6-9 for the gravimetric and particle size analyses, respectively. Individual data are shown in these tables along with an average for each test performed.

As can be seen from Tables 6-8 and 6-9, CMA has the highest potential for dust resuspension of the three deicing compounds tested. Approximately 35% of the total deicer applied ends up as solid residue on the test surface with over 50% of this material consisting of silt size particles. Thus, CMA appears to have the highest potential for PM_{10} emissions as compared to the other deicers tested.

Table 6-8 is also very informative with respect to the potential for post-storm runoff. As shown, rock salt has the highest wet runoff potential (i.e., average of 30.2%) of the three deicers tested with CMA being a close second. $CaCl_2$ was shown to have little or no potential for post-storm runoff. These results could have substantial implications in the design of future snow and ice control programs which may rely on pretreatment to prevent rather than mitigate the loss of traction on paved roadways.

6.4 DATA ANALYSIS

The following subsections provide the results of MRI's analysis of the test data derived from the experimental program. Each test type is discussed separately.

6.4.1 Abrasive Tests

One of the objectives of this study was to determine whether the apparent degradation (i.e., grinding) produced by simulated traffic could be quantitatively related to material properties (e.g., L.A. abrasion loss, quartz content, etc.). In order to perform this analysis, it first was necessary to derive an indicator of the change in particle size distribution between the initial and post test states. There are a number of different formulations that could be used. One simple example, would be the ratio of silt content after a given number of passes to the initial material silt content. This study adopts a somewhat broader indicator—the change in material mass median diameter (MMD) between the initial state and final state (i.e., after 65,000 simulated vehicle passes). The principal advantage of using the mass median diameter over a single size "cut" (e.g., silt content) is that by definition the MMD considers the entire size distribution. In this sense the MMD should better reflect the overall impact/degradation effects of simulated traffic on the various test materials.

Table 6-10 presents both the MMD data and the change in MMD, expressed as a ratio, for each of the five valid track tests. The MMD data were developed by fitting the mechanical sieving results to a presumed lognormal distribution. (Note that the data presented do not include Tests 7 and 8 as indicated in Section 6.2.4.1—these tests

TABLE 6-8. RESULTS OF SMALL SCALE EXPERIMENTS

Deicer tested	Block ID	Original amount applied (g)	Application rate (g/m^2)[a]	Amount of sample recovered by method[b]								
				Dry recovery		Wash No. 1		Wash No. 2		Wash No. 3		Total % recovered
				grams	weight %	grams	weight %	grams	weight %	grams	weight %	
Rock salt[c] (NaCl)	A	4.11	135	0.3786	9.2	0.9000	22	0.2818	6.9	0.1321	3.2	41
	B	4.11	135	0.4600	11	0.8630	21	0.2133	5.2	0.0940	2.3	40
	C	4.11	135	0.2501	6.1	0.8511	21	0.2508	6.1	0.1032	2.5	35
	Average	4.11	135	0.3629	8.8	0.8714	21	0.2486	6.1	0.1098	2.7	39
CaMg Acetate[d]	1	4.11	135	1.408	34	0.8206	20	0.1117	2.7	0.0421	1.0	58
	2	4.11	135	1.502	37	1.004	24	0.1341	3.3	0.0330	0.80	65
	Average	4.11	135	1.455	35	0.9122	22	0.1229	3.0	0.0376	0.91	62
Calcium chloride[e]	A	4.11	135	0.0324	0.79	0.2062	5.0	0.0996	2.4	0.0835	2.0	10
	B	4.11	135	0.0335	0.81	0.2895	7.0	0.1398	3.4	0.1018	2.5	14
	C	4.11	135	0.0250	0.61	0.2208	5.3	0.1540	3.8	0.1038	2.5	12
	Average	4.11	135	0.0303	0.74	0.2388	5.8	0.1311	3.2	0.0964	2.3	12

[a] Equivalent to an initial application of 500 lbs/lane mile plus five (5) reapplications of 250 lbs/lane mile according to AASHTO recommendations for deicing salts.

[b] Dry recovery was performed by mechanical removal of the surface material followed by dry vacuuming. Wet recovery was conducted by flushing the surface with hot deionized water (see text for details). Wt. % = percent of original sample recovered from surface.

[c] Block A = mostly large salt particles; Block B = mixture of large and small particles; Block C = mostly small salt particles.

[d] Homogeneous round pellets. No melting of ice was observed after application of CMA; ice melted by combination of warm water and heat lamps.

[e] Homogeneous round pellets of Peladow®.

TABLE 6-9. PARTICLE SIZE DATA FOR SMALL SCALE EXPERIMENTS (SONIC SIEVING RESULTS)

Deicer tested	Sample ID	Total dry loading (g/m^2)[a]	Percent < stated size[b]		
			< 75 μmP	< 53 μmP	< 20 μmP
Rock salt (NaCl)	Block A	12	71	51	6.8
	Block B	15	62	42	4.9
	Block C	8.2	58	44	29
	Average	12	63	46	13
CaMg Acetate	Block 1	46	55	39	6.5
	Block 2	49	56	40	3.1
	Average	48	56	39	4.8
Calcium chloride ($CaCl_2$)[d]	Block A	1.1	NA	NA	NA
	Block B	1.1	NA	NA	NA
	Block C	0.82	NA	NA	NA
	Average	0.99	—	—	—

[a] Calculated from amount of material recovered from surface by mechanical removal followed by dry vacuuming. Total initial loading applied to surface = 135 g/m^2 (4.11 g of deicer).

[b] μmP = micrometers physical particle diameter. NA = not available (insufficient sample for analysis).

[c] Peladow® pellets.

TABLE 6-10. MASS MEDIAN DIAMETER (μmP) OF ABRASIVE SAMPLES TESTED ON WHEEL PASSAGE MACHINE

Test No.	Sample identification	Initial MMD	Post-test MMD	Change (initial/post-test)
1	Holiday Sand & Gravel Ice control sand	900	190	4.74
2	Maine DOT Presque Isle Stockpile	2,400	10	240
3	Steamboat Springs Scoria	1,500	37	40.5
4	Columbia Falls New	7,000	350	20.0
5	Colorado APCD Washed squeege	4,800	95	50.5

showed as a net gain in the material mass recovered from the test track, apparently the result of track resurfacing.)

To determine whether quantitative relationships exist between change in MMD and material properties, both linear correlation and simple regression were used. Table 6-11 shows the correlations between MMD change and material property. Note that all data were transformed using natural logarithms, prior to computing the correlations.

TABLE 6-11. LINEAR CORRELATION BETWEEN MMD CHANGE AND TEST MATERIAL PROPERTIES

Material property	Correlation with MMD change
LA abrasion loss	0.866
Wet aggregate durability	−0.298
Quartz content	0.084
Vickers hardness	−0.696
Unit weight	−0.479
Void fraction	0.109
Particle shape index	0.555

Based on the above correlations, it is evident that degradation produced by simulated traffic (i.e., MMD change) is best related to abrasion loss. Figure 6-8 presents this correlation graphically. Alternatively, the relationship can be presented in the following regression format.

$$\Delta \text{ MMD} = 5.46 \bullet (\text{Abrasion Loss})^{1.35} \qquad (6\text{-}1)$$

This relationship accounts for 75% of the variation (i.e., $R^2 = 0.75$) in MMD change over the five valid test runs.

6.4.2 Deicer Tests

The results of the single deicer test conducted on the wheel passage machine were analyzed to determine if any discernable trends could be derived from the data. This analysis yielded no conclusions which could be considered physically meaningful. Therefore, these results were combined with other limited data from the small block experiments and analyzed further.

To determine the amount of deicer potentially available for resuspension as PM_{10} on paved roadways, a mass balance was performed using data from tests of MO DOT rock salt. In this analysis the total amount of sample recovered from the test surface (i.e., track or test block) was compared to that originally applied. The NaCl and silt content of the samples were then combined to estimate the percent of the total NaCl in the silt size range. (Note that the remaining material recovered from the wheel passage machine was probably composed of tire wear, track debris, and other insoluble material generated during testing.) The results of this analysis are shown in Table 6-12.

As noted from Table 6-12, the mass balance for the wheel passage tests and small block tests compare favorably with one another. These results indicate that between 3% and 6% of the total NaCl applied (i.e., 60 to 120 lb/ton) ends up as silt size particles and thus available for resuspension as PM_{10}. (Note that the NaCl applied = total deicer applied less the percent insoluble matter in the deicer.) Comparing these values to the percent insoluble matter in the original deicer (i.e., average of 0.77%) would indicate that substantially more silt (i.e., a factor of > 5) is potentially created by the application of rock salt than could be estimated from material properties alone.

Using the results of the wheel passage test shown in Table 6-12, the PM_{10} emissions associated with the application of rock salt were estimated using the current AP-42 emission factor (Equation 1-1). This estimate was compared to similar emissions determined by the calculation scheme developed during the "gap filling" exercise of Grelinger et al. (1988). Here the following assumptions were used: a 1-mi stretch of 4-lane road; a lane-width of 12 ft; an average daily traffic (ADT) of 40,000 (i.e., 10,000 vehicles/lane-day); and one application of rock salt at a rate of 500 lb/lane-mile plus five reapplications at 250 lb/lane-mile performed within a 24-hour period.

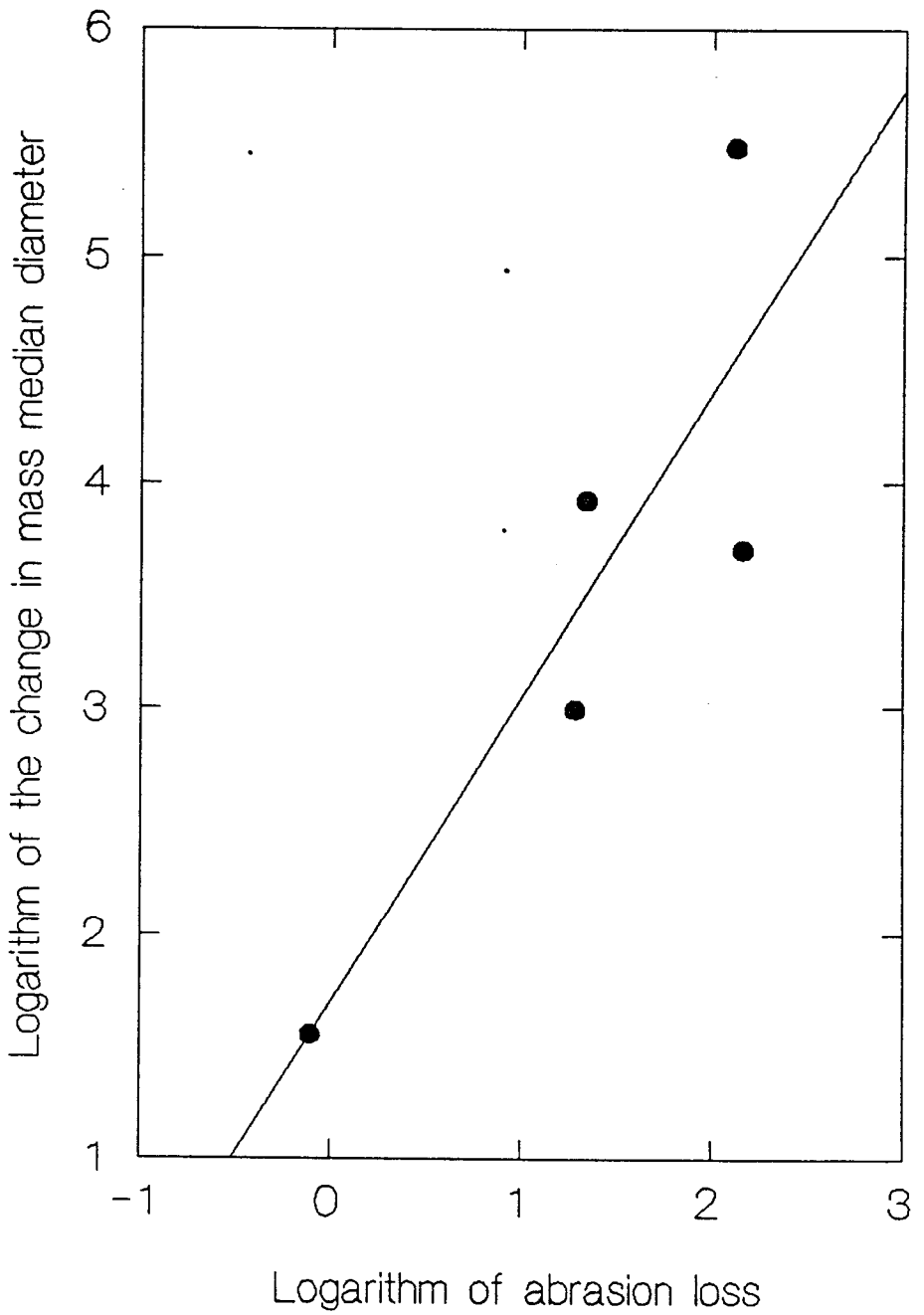


Figure 6-8. Correlation of change in mass median particle diameter with LA abrasion loss.

TABLE 6-12. MASS BALANCE FOR ROCK SALT (NaCl) TESTS

Test configuration	Total NaCl applied to test surface (gm)[a]	Total dry sample recovered from test surface		Total NaCl in sample recovered		Average silt content of sample recovered (Weight %)	Total NaCl on test surface in silt size range[c]	
		Grams	Weight %	Grams	Weight %[b]		Grams	Weight %
Wheel passage machine	101	23.7	23.3	6.99	6.89	48.1[d]	3.36	3.31
Small block tests	4.08	0.363	8.89	0.363[e]	8.89	63.5[f]	0.230	5.65

[a] Weight of deicer less the percent insoluble matter.

[b] Weight % = Weight percent of total NaCl applied to test surface.

[c] Material considered available for resuspension as PM_{10} using AP-42 predictive equation.

[d] Weighted average calculated from data in Table 6-6.

[e] All material recovered assumed to be NaCl.

[f] Arithmetic average shown in Table 6-9. Three significant figures.

The above assumptions, together with Equation (1-1) and Table 6-12 result in an emission rate of 470 lb/lane-day. This should be compared to approximately 8.8 lb/lane-day for similar calculations performed using the "gap filling" document. The great disparity (i.e., a factor of 52) between the two estimates stresses the need for an emission factor based on actual field testing.

Another factor of note pertains to the contribution of paving and tire wear to the increase in silt content due to application of antiskid deicers. These materials normally contribute to the total silt loading on paved roads to some extent. However, what is not currently known is how wear debris change as a result of deicer application. Therefore, a total increase in silt loading of 6% to 11% (i.e., % total sample recovered x silt content) might be expected to more appropriately account for additional pavement/tire debris generated by the use of deicers on paved roads.

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

A number of conclusions and recommendations were developed in the preparation of this guidance document. These are presented in the following subsections.

7.1 CONCLUSIONS

The following conclusions were reached as part of Phase 1:

1. The application of antiskid materials causes a temporary, but substantial increase in surface silt loading on paved roads.

2. The level of PM_{10} emissions generated by traffic resuspension of (dry) roadway surface dust is directly dependent on the surface silt loading.

3. The tendency for an antiskid abrasive to generate silt-sized particles is a function of its durability.

4. Particles smaller than 50 mesh (approximately 300 μm in physical diameter) have been found to be relatively ineffective in increasing the coefficient of friction on paved roads.

5. Of all the durability test methods surveyed, the Los Angeles abrasion test seems to be the most appropriate for the measurement of overall aggregate durability.

6. A good quality, washed construction aggregate (e.g., sand) appears to be the best choice with respect to maximum effectiveness as an antiskid abrasive with low silt generation potential.

7. Salt is effective as an antiskid material above about 20°F with minimal cleanup requirements but with significant (albeit poorly known) potential for PM_{10} emissions as well as other adverse environmental effects such as corrosivity and ecological stress.

8. Antiskid materials are frequently applied at loadings well above recommended levels because of public perception that effectiveness is proportional to the visible amount of surface loading.

9. Excess silt loadings (and thus PM_{10} emissions) associated with antiskid materials result primarily from over application and noncompliance with recommended fines and durability specifications for antiskid abrasives.

The following conclusions were reached as part of Phase 2 of the study:

1. Antiskid abrasives typically used in PM_{10} nonattainment areas can be statistically grouped into five basic categories (or clusters) based on the eight key material properties measured in the program as follows:

   - C1—Materials exhibiting relatively low initial silt (0.99% to 4.9%) and quartz (10 to 36 mmol/L) contents; other material properties near the overall means.

   - C2—Coarse and soft materials as indicated by high particle shape (21 to 27) and void fraction (45% to 46%) indices along with relatively low unit weight (860 to 1200 kg/m^3) and Vickers hardness (340 to 460 kg/mm^2) values.

   - C3—Materials that exhibit both high quartz (150 to 190 mmol/L) and high silt (4.1% to 4.9%) contents; other material properties near the overall means.

   - C4—Relatively hard materials as indicated by low silt content (0.02% to 0.25%), low abrasion loss (0.90% to 4.0%), and high values for the Vickers hardness test (550 to 1200 kg/mm^2).

   - C5—Finely divided materials that are easily abraded; indicated by high silt content (4.3% to 8.9%) and high abrasion losses (7.1% to 17%).

2. Based on the limited data collected in the simulated traffic tests, materials in cluster C4 tended to have the lowest overall potential for the generation of PM_{10} emissions as compared to other groups. Alternately, the material from cluster C5 showed the greatest potential for PM_{10} emissions in these tests as predicted by the current AP-42 emission factor equation.

3. In the small scale experiments of three chemical deicers, calcium magnesium acetate (CMA) had higher PM_{10} emissions potential than rock salt and calcium chloride (i.e., 27 g/m^2 sL for CMA vs. 7.6 g/m^2 and < 1 g/m^2 for NaCl and $CaCl_2$, respectively). On the other hand, rock salt had the highest post-storm

(wet) runoff potential (i.e., 30% wet recovery for NaCl vs. 26% and 11% for the other deicers) in these tests.

4. The best overall indicator of silt generation potential found in the five valid traffic tests of abrasives appears to be Los Angeles abrasion loss. However, Vickers hardness and particle shape index may also be useful in predicting overall material behavior for the abrasives tested.

5. Increases in surface silt loading for rock salt were found to be a factor of > 5 higher than could be predicted from the insoluble matter in the material alone.

6. PM_{10} emissions calculated using the traffic test results for rock salt were a factor 50 higher than previously estimated. This underestimation could affect the preparation and/or implementation of PM_{10} SIPs for certain state and local jurisdictions.

7. Contributions to silt loading from enhanced tire and pavement wear could not be quantified from existing data.

7.2 FINAL MATERIAL SELECTION CRITERIA

It is difficult to formulate definitive quantitative selection criteria for antiskid materials from available data. Still, one can provide general ranges of key parameters for material groups (clusters) which exhibit high or low increases in silt content in service, thus implying high or low durability. In this sense, materials in these ranges could be classified as "acceptable" and "nonacceptable." Currently only antiskid abrasives have a data base adequate to provide selection criteria based on material properties. These are shown in Table 7-1.

TABLE 7-1. REVISED SELECTION CRITERIA FOR ANTISKID ABRASIVES

		Acceptable materials[a]		Unacceptable materials[b]	
Measurement parameter	Units	Range of values	Mean	Range of values	Mean
Modified Los Angeles abrasion loss	Weight %	0.9-4	3	7-17	11
Initial silt content[c]	Weight %	0.02-0.3	0.1	4-9	6
Vickers hardness	kg/mm^2	500-1,200	1,000	400-1,000	800
Particle shape index	Dimensionless	6.3-15	10	6.5-13	9

[a] Based on data for cluster C4.

[b] Based on data for cluster C5.

[c] This parameter is coupled to LA abrasion loss and thus included in the material selection criteria.

Table 7-1 lists the upper and lower bounds of LA abrasion loss, initial silt content, Vickers hardness, and particle shape index for acceptable and nonacceptable materials, respectively. If the properties of a particular material fall between the ranges indicated, the acceptability of the material must be considered as "questionable," and good engineering judgment should be employed before the material is used for ice and snow control in a PM_{10} nonattainment area. Other qualitative factors discussed in Section 4 of this report can also be incorporated into the decision-making process. .

To further assist in the decision-making process, a decision "tree" has been developed for material selection as shown in Figure 7-1. As a starting point in this analysis, the service conditions must first be defined. These conditions take into account road surface characteristics (e.g., slope, pavement composition, presence of curbs/shoulders), traffic parameters (e.g., volume, route speed, acceleration/deceleration), and meteorological conditions surrounding snow/ice events (e.g., temperature, evaporation rates). The service conditions will also vary from location to location within a particular geographical area.

From that point, candidate materials can be evaluated based on silt generation potential, cost, availability, etc., and the most promising material(s) selected for field study. The above analysis of the acceptability of candidate materials is highly dependent on local conditions and should be performed on a case-by-case basis. The criteria shown in Table 7-1 and the decision tree shown in Figure 7-1 should assist in the overall selection process.

7.3 RECOMMENDATIONS

Based on study results, the following recommendations for further investigation were developed:

1. A revised Los Angeles abrasion test method should be developed to improve precision and better determine the silt generation potential of antiskid abrasives. Applicable modifications to this method are discussed in Section 3.5.1.

2. The current method for field measurement of silt loading should be subjected to collaborative testing under wintertime snow/ice control conditions to determine existing method reproducibility and any needed modifications to improve reproducibility.

3. Additional study of surface loading dynamics following the application of antiskid materials is needed in order to better understand the PM_{10} emission impacts associated with various antiskid program scenarios. This could be accomplished by a well designed and implemented surface sampling program performed before, during, and after individual storm events at selected locations in PM_{10} nonattainment areas.

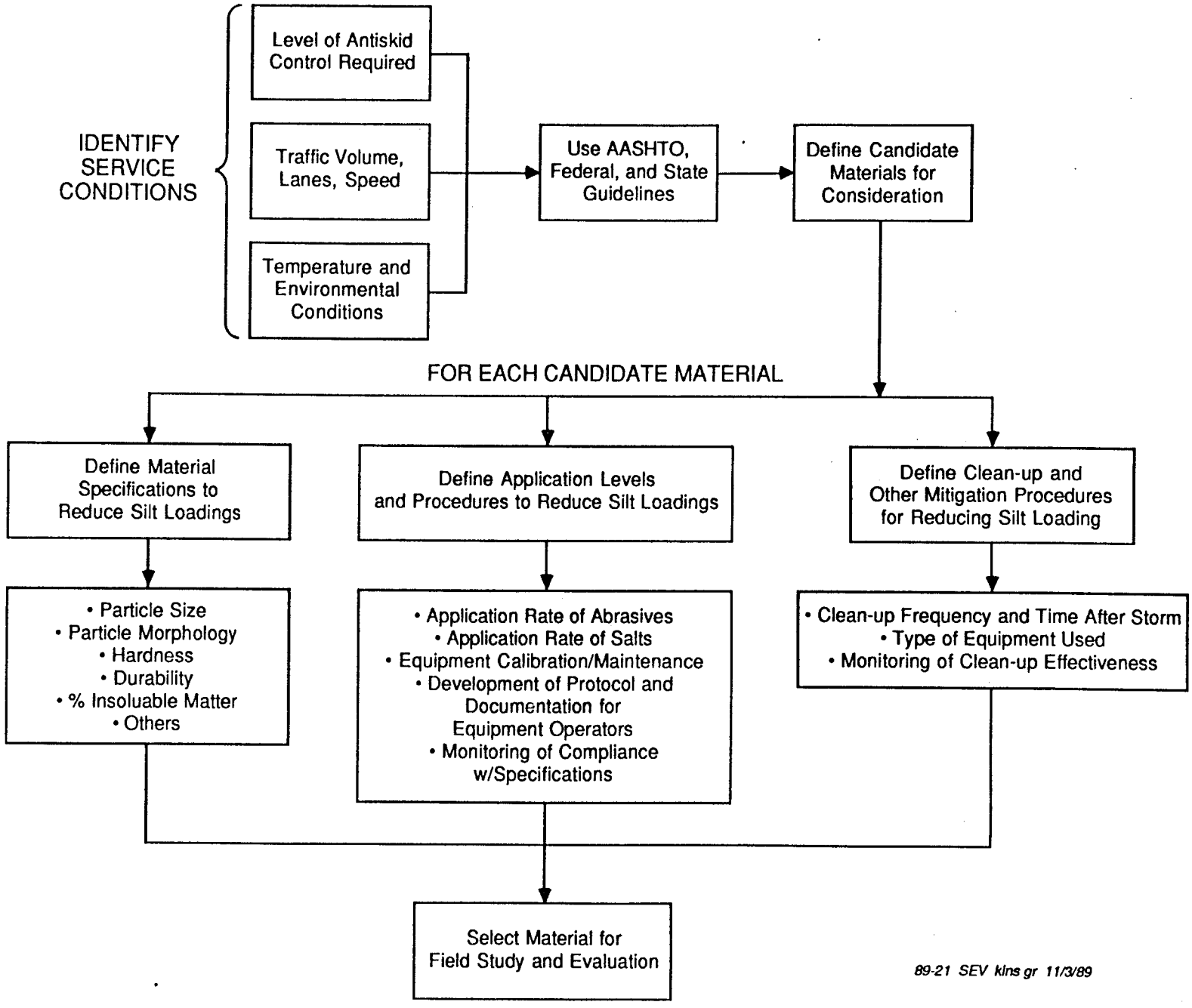


Figure 7-1. Decision "tree" for antiskid material selection.

4. Further study of the fate and transport of salt(s) applied for antiskid control is needed to determine an applicable emission factor based on field testing. A mass balance approach using a combination of surface and air sampling should be used in this study to quantify the PM_{10} emissions associated with deicing salts.

5. Common post-storm cleanup practices should be studied to determine the net air quality benefits of cleanup at various points after application as a function of antiskid material specifications.

6. The contribution of tire and pavement wear to surface silt loading (sL) should be quantified for the application of antiskid abrasives and deicers. If increases in sL are observed, methods for prevention/mitigation should be investigated.

SECTION 8

REFERENCES

American Association of State Highway and Transportation Officials (1964). Standard Method of Test for Production of Plastic Fines in Aggregates. Method T-210-64, in *Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part II: Methods of Sampling and Testing*, Fourteenth Edition, Washington, D.C., August 1986.

American Association of State Highway and Transportation Officials (1976). AASHTO Maintenance Manual. 1st Edition, Washington, D.C., February.

American Association of State Highway and Transportation Officials (1983). Standard Method of Test for Resistance of Abrasion of Small Size Coarse Aggregate by Use of the Los Angeles Machine. Method T 96-83, in *Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part II: Methods of Sampling and Testing*, Fourteenth Edition, Washington, D.C., August 1986.

American Association of State Highway and Transportation Officials (1984). Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates. Method T 27-84, in *Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part II: Methods of Sampling and Testing*, Fourteenth Edition, Washington, D.C., August 1986.

American Association of State Highway and Transportation Officials (1985a). Standard Method of Amount of Material Finer than 75 μm Sieve in Aggregate. Method T 11-85, in *Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part II: Methods of Sampling and Testing*, Fourteenth Edition, Washington, D.C., August 1986.

American Association of State Highway and Transportation Officials (1985b). Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate. Method T-104, in *Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part II: Methods of Sampling and Testing*, Fourteenth Edition, Washington, D.C., August 1986.

American Society of Testing and Materials, Subcommittee C09.02.06 (1969). Standard Descriptive Nomenclature of Constituents of Natural Mineral Aggregates. Method C 294-69, Philadelphia, Pennsylvania.

American Society of Testing and Materials, Subcommittee C09.03.05 (1983). Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate. Method C 88-83, Philadelphia, Pennsylvania.

American Society of Testing and Materials, Subcommittee C09.03.05 (1984a). Standard Method for Sieve Analysis of Fine and Coarse Aggregates. Method C 136-84a, Philadelphia, Pennsylvania.

American Society of Testing and Materials, Subcommittee D04.31 (1984b). Standard Specification for Sodium Chloride. Method D 632-84, Philadelphia, Pennsylvania.

American Society of Testing and Materials, Subcommittee C09.02.06 (1985a). Standard Practice for Petrographic Examination of Aggregates for Concrete. Method C 295-85, Philadelphia, Pennsylvania.

American Society of Testing and Materials, Subcommittee C09.03.05 (1985b). Standard Specification for Concrete Aggregates. Method C 33-85, Philadelphia, Pennsylvania.

American Society of Testing and Materials, Subcommittee D04.51 (1985c). Standard Test Method for Aggregate Durability. Method D 3744-85, Philadelphia, Pennsylvania.

American Society of Testing and Materials, Committee E-15 (1986). Standard Test Method for Chemical Analysis of Sodium Chloride. Method E 534-86, Philadelphia, Pennsylvania.

American Society of Testing and Materials, Subcommittee C09.03.05 (1987). Standard Test Method for Materials Finer than 75 μm (No. 200) Sieve in Mineral Aggregates by Washing. Method C 117-87, Philadelphia, Pennsylvania.

American Society of Testing and Materials, Subcommittee C09.03.05 (1989). Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine. Method C 131-89, Philadelphia, Pennsylvania.

American Society of Testing and Materials, Committee E-4 (1989). Standard Test Method for Microhardness of Materials. Method E 384-89, Philadelphia, Pennsylvania.

Anonymous (1979). Aggregates for Road Pavements. *Hwys. Pub. Wks.*, 47:1835, 16-19, October.

Anonymous (1988). "How Highway Departments Deal with Nature's Forces," *Better Roads*, 58:1, 19-21, January.

Baboian, R. (1988). The Automotive Environment. *Automotive Corrosion by Deicing Salts*, National Association of Corrosion Engineers, Houston, Texas.

Blackburn, R. R., et al. 1978. "Physical Alternatives to Chemicals for Highway Deicing," U.S. Department of Transportation, Federal Highway Administration, Washington, D.C.

Brant, L. A. (1972). Winter Sanding Operations and Air Pollution. *Public Works*, 103:9, 94-7, September.

Brown, M. G. (1988). Corrosion of Highway Appurtenances Due to Deicing Salts. *Automotive Corrosion Due to Deicing Salts*, National Association of Corrosion Engineers, Houston, Texas.

Chollar, B. H. (1984). Federal Highway Administration Research on Calcium Magnesium Acetate—An Alternative Deicer. *Public Roads*, 47:4, 113-118.

Connor, P. E., and R. Gaffi (1982). Optimum Sand Specifications for Roadway Ice Control. State of Alaska, Department of Transportation and Public Facilities, Fairbanks, Alaska, June.

Cowherd, Chatten, et al. (1977). Quantification of Dust Entrainment from Paved Roadways. EPA-450/3-77-027, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, July.

Dhir, R. K., et al. (1971). Study of the Aggregate Impact and Crushing Value Tests. *Hwy. Engr.*, 18:11, 17-27, November.

Dubberke, W., and V. J. Marks (1985). The Effect of Deicing Salt on Aggregate Durability. *Transportation Research Record*, 1031:27-34.

Dunn, S. A., and R. U. Schenk (1980). Alternatives to Sodium Chloride for Highway Deicing. *Transportation Research Record 776*, 12-15.

Eck, R. W., et al. (1986). Natural Brine as an Additive to Abrasive Materials and Deicing Salts. WVDOH Research Project 75, West Virginia Department of Highways, May.

Furbush, M. A. (1972). Relationship of Skid Resistance to Petrography of Aggregates. PB-220 071, Federal Highway Administration, Washington, D.C., July.

Goswami, S. C. (1984). Influence of Geological Factors on Soundness and Abrasion Resistance of Road Surface Aggregates: A Case Study. *Bull. Inter. Assn. Eng. Geol.*, 30, 59-61, December.

Grelinger, M. A., et al. (1988). Gap Filling PM_{10} Emission Factors for Selected Open Area Dust Sources. Final Report, EPA Contract No. 68-02-4395, Work Assignment 6, Midwest Research Institute, Kansas City, Missouri, February 9.

Havens, J. H., and D. C. Newberry (1982). Aggregate Shape and Skid Resistance. UKTRP-82-1, Kentucky Transportation Cabinet, Frankfort, Kentucky, January.

Hegmon, R. R., and W. E. Meyer (1968). The Effectiveness of Antiskid Materials. *Highw. Res. Rec. 227*, Highway Research Board, NAS-NRC, 50-56.

Helmers, G., and U. Ytterbom (1986). Effects of Salt on the State of Dirtiness of the Road. NTIS No. PB86-201167, Statens Vaeg-och Trafikinstitut, Sweden.

Hudec, P. P. (1984). Quantitative Petrographic Analysis of Aggregate. *Bull. Inter. Assn. Eng. Geol.*, 29, 381-385, June.

Iowa Department of Transportation (1980). Deicing Practices in Iowa: An Overview of Social, Economic, and Environmental Implications. Report No. 17-T68PP/9:D368, Planning and Research Division, Office of Project Planning Highway Division, Office of Maintenance, for the Iowa General Assembly House of Representatives, Des Moines, Iowa, January.

Jorgensen, R., et al. (1964). Nonchemical Methods of Snow and Ice Control on Highway Structures. Report No. 4, National Cooperative Highway Research Program, Highway Research Board, Washington, D.C.

Kaufmann, D. W. (1968). *Sodium Chloride—The Production and Properties of Salt and Brine*, American Chemical Society, Hafner Publishing Company, New York.

Keyser, J. H. (1973). Deicing Chemicals and Abrasives: State of the Art. *Highw. Res. Rec. 425*, Highway Research Board, 36-51.

Kinsey, J. S., and R. M. Coveney, Jr. (1986). Mineral Characterization of Selected Soil Samples. Final Report, MRI Project 8466-L to New Mexico State University, Las Cruces, New Mexico, January 14.

Legislative Research Council (1965). The Use and Effects of Highway Deicing Salts, *Commonwealth of Massachusetts*, Boston, Massachusetts, January.

McDonald, R. D. (1981). Automotive Underbody Corrosion Testing.

McElroy, A. D., et al. (1988). Comparative Evaluation of Calcium Magnesium Acetate and Rock Salt, *Transportation Research Record 1157*, 12-19.

Minsk, D. L. (1981). Snow Removal Equipment. in *Handbook of Snow-Principals, Processes, Management, and Use*. Pergamon Press, New York.

Murray, Donald M., and U. F. W. Ernst (1976). An Economic Analysis of the Environmental Impact of Highway Deicing. EPA-600/2-76-105, U.S. Environmental Protection Agency, Cincinnati, Ohio, May.

Norburg, C. H. (1981). The Washington Degradation Test Maine Variation. Technical Paper 81-9, Materials Research Division, Maine Department of Transportation, Augusta, Maine.

Oeberg, G., et al. (1985). Experiments With Unsalted Roads. NTIS No. PB86-177409, Statens Veag-och Trafikinstitut, Sweden.

PEDCo Environmental, Inc. (1981). Denver Demonstration Study. Colorado Division of Air Pollution Control, Denver, Colorado, October.

Rainiero, J. M. (1988). Investigation of the Ice-Retardant Characteristics of Verglimit-Modified Asphalt. *Transportation Research Board*, 1157, 44-53.

Salt Institute (1984). Survey of Salt, Calcium Chloride, and Abrasive Use in the United States and Canada. Alexandria, Virginia.

Salt Institute (1986). *The Snowfighter's Handbook*. Alexandria, Virginia.

Salt Institute (1989). Salt Institute Statistical Report Analysis, Total Sales by United States Members. Alexandria, Virginia.

Schneider, T. R. (1959). Schneeverwehungen und Winterglatte. Interner Bericht Nr. 302. Eidgenossisches Institut fur Schnee-und Lawinenforschung.

Schneider, T. R. (1960). The Calculation of the Amount of Salt Required to Melt Ice and Snow on Highways. National Research Council of Canada, Technical Translation No. 1004.

Sheehy, J. P., et al. (1968). Handbook of Air Pollution. 999-AP-44, U.S. Public Health Service, Washington, D.C.

Slick, D. S. (1988). Effects of Calcium Magnesium Acetate on Pavements and Motor Vehicles. *Transportation Research Record 1157*, 27-30.

Stiffler, A. K. (1969). Relation Between Wear and Physical Properties of Roadstone. *Hwy. Res. Board Special Reports*, 101, 56-68.

Transportation Research Board (1974 and 1984). Minimizing Deicing Chemical Use. N24 Final Report, Washington, D.C.

U.S. Environmental Protection Agency (1972). A Search: New Technology for Pavement Snow and Ice Control. EPA-R2-72-125, Office of Research and Monitoring, U.S. Environmental Protection Agency, Washington, D.C., December.

U.S. Environmental Protection Agency (1985). Compilation of Air Pollution Emission Factors, AP-42. U.S. Environmental Protection Agency, Research Triangle Park, North Carolina.

Welch, Bob H., et al. (1976). Economic Impact of Highway Snow and Ice Control—State of the Art. Report No. FHWA-RD-77-20, Utah Department of Transportation Research and Development Section, September.

Wood, F. (1983). Noncorrosive Winter Maintenance Workshop, Frank Wood of Salt Institute. Method 10-26-83, in *Proceedings of the Northstar Workshop on Noncorrosive Winter Maintenance*, FHWA/MN/RD-84/03, Federal Highway Administration, Washington, D.C., October.

Wood, F. (1983). Proceedings of the Northstar Workshop on Noncorrosive Winter Maintenance (Technical Presentations). Report No. FHWA/MN/RD-84/03, Minnesota Department of Transportation, 56-67, October.

Woodside, A. R., and R. A. Peden (1983). Durability Characteristics of Roadstone. *Quarry Mgt. Prod.*, 10:8, 493-494/497-498, August.

Wyoming Highway Department Maintenance Manual. (1984). Wyoming Department of Transportation.

APPENDIX A

SURVEY PROCEDURES

The following sections outline the literature search and telephone survey performed during the study.

A.1 LITERATURE SEARCH

The results of three literature searches were examined for references pertinent to the current study. From a previous program, MRI had compiled a data base of abstracts and citations on: ice disbonding; laboratory studies on ice; salt effects on soils, pavements, steel corrosion, and plants; and the properties and uses of deicing chemicals. The abstracts had been compiled from the STN CA file, NTIS, and TRIS data bases. The most recent references in the MRI data base were published in 1987.

Additional literature searches were done in August and September 1989 on the hardness and tendency of antiskid materials to produce fines. The more extensive on-line search in August focused on the TRIS data base, although a few retrievals were made from the NTIS data base. The strategy combined the concept of the materials (key words: antiskid or abrasives or sand or stone or cinders or slag) used for highway/road/street snow or ice removal (controlling or deicing or deicers or salt or melt) with key words for the following concepts:

- Skid resistance (including coefficient of friction and traction).
- Application/spreading rates or costs.
- The dustiness concept (key words: attrition or fines or dusts or silt or gradation or grade or sizing or sieve or sieving or screening or grain size or granulometry or durability or stability or petrography or degradation).
- Cleaning or flushing the materials.
- Alternatives or substitutes.

The strategy, of course, allowed for appropriate truncation and proximity operators for the key word relationships.

In September, the data bases Compendex Plus (Engineering Abstracts and Engineering Meetings), TRIS, IHS International Standards and Specifications, and Standards and Specifications were searched for reviews on aggregate hardness testing procedures. The search combined the following three sets of key words with the key word review:

1. Road/highway/street use of aggregate.
2. Test or standard or specification.

3. Hardness or Mohs or Knoop or scleroscopy or crush resistance or wear resistance or abrasion resistance.

From the above search 121 documents were identified, collected, and reviewed for pertinent data. The documents collected are listed under references in Section 8 or in the bibliography in Appendix B.

A.2 TELEPHONE SURVEY

Nine states and two municipalities were surveyed by telephone (some with multiple contacts) to gather information on current ice and snow control practices, especially as related to the impact of antiskid materials on dust production. The telephone survey was based on the questionnaire found in Figure A-1. This six-page form permitted the recording of comprehensive information on types of deicing chemicals and abrasives, factors associated with selection of particular antiskid measures, application methods and rates, and cleanup operations. Often the state or municipal official surveyed had partial information, so only the appropriate sections of the questionnaire were completed. Several states also submitted specifications for purchase of antiskid materials.

Early in the program it was determined that the South Dakota Department of Transportation was accumulating information on abrasives. Over 20 states had responded with information on specifications for particle size distributions and other physical characteristics of abrasives. The questionnaire used in this effort appears in Figure A-2.

The purpose of the South Dakota survey was to develop background information for a new specification for antiskid aggregates based on reducing the number of broken windshield complaints and achieving high skid resistance. The sand in the South Dakota survey was classified into five categories: pit run sand, screened pit run sand, crushed pit run aggregate, crushed quarry aggregate, and other. Also, some respondents provided their particular material specifications as attachments. The results of the telephone and South Dakota surveys are provided in Section 2.1 of the main report.

TELEPHONE SURVEY QUESTIONNAIRE

Selection and Usage of Anti-Skid Materials for Ice and Snow Control

Agency Surveyed:_____ Date:_____

Person Contacted:_____ Tele. No. (___)_____

Mailing Address of Agency:_____

_____

1. What types and amounts of deicing chemicals and abrasives have you used in each of the last 3 years? How many lane-miles of road were treated by each type of chemical and abrasive? What is the cost of these materials and the "nominal" application rate (lbs/lane-mile)?

YEAR	MATERIAL TYPE	QUANTITY (TONS OR GALLONS)	LANE-MILES TREATED	UNIT COST ($/TON) OR TOTAL ANNUAL COST ($K)	NOMINAL APPLICATION RATE (LBS/ LANE-MILE)
_____	_____	_____	_____	_____	_____
	_____	_____	_____	_____	_____
	_____	_____	_____	_____	_____
	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
	_____	_____	_____	_____	_____
	_____	_____	_____	_____	_____
	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
	_____	_____	_____	_____	_____
	_____	_____	_____	_____	_____
	_____	_____	_____	_____	_____

Figure A-1. Telephone survey questionnaire.

2. Are chemicals and abrasives mixed prior to application and, if so, in what proportions? _____

_____

_____

_____

3. What factors (e.g., cost, availability, effectiveness, etc.) are used to select a particular abrasive or chemical for use in ice and snow control?

a. Cost Considerations:

- Abrasives: _____

_____

- Chemicals: _____

_____

b. Availability Considerations: What are the sources of the materials currently used?

- Abrasives: _____

_____

- Chemicals: _____

_____

c. Driving Improvement Effectiveness:

MATERIAL TYPE	ROAD CONDITION	EFFECTIVENESS

How do you define effectiveness? _____

_____

Figure A-1 (Continued)

d. Dust Generation Potential:

_____

_____

_____

e. Other Considerations (e.g., durability; temperature; corrosivity; environmental conditions; etc.):

_____

_____

_____

4. What materials, other than those currently being used, have been considered for use in ice and snow control?_____

_____

Why were these rejected?_____

_____

5. Do you have specifications (e.g., gradation, durability, etc.) and standard test methods for the abrasives and chemicals used for ice & snow control? _____
If so, what do they generally consist of? _____

_____

_____

_____

6. Could you send a copy of the above specifications and test methods by first class mail? _____

7. What is the basis for a particular road being treated (traffic volume, rural vs. urban routes, school route, public demand, accident rates, etc.)? _____

_____

_____

8. Are abrasives/chemicals applied at different rates? _____ If so, what is the basis for selecting the application rate? _____

_____

_____

Figure A-1 (Continued)

9. Have directives been published and distributed to operating personnel regarding the current policy on the use of abrasives and chemicals for ice and snow control? _____ If so, could you send a copy by first class mail? _____

10. Do you require detailed reports by equipment operators on the quantity of abrasives and chemicals used? _____ If so, is this information correlated with temperature, traffic, snowfall, humidity, or other factors effecting the quantities used? _____

_____

_____

11. What type of distribution equipment is used to apply abrasives/chemicals to different road types?

	MATERIALS TYPE	DISTRIBUTION EQUIPMENT
a. State Highways (rural areas):	_____	_____
	_____	_____
b. Expressways:	_____	_____
	_____	_____
c. City Streets:	_____	_____
	_____	_____
d. Major Intersections/Bridges:	_____	_____
	_____	_____
e. Other _____:	_____	_____

12. How are the application rates and spreading pattern set on the above equipment?

_____

_____

_____

13. Is abrasive/chemical use and durability checked after the storm to determine the effectiveness of treatment, adherence to application rate specifications, generation of fines, etc.? _____ If so, how is this performed? _____

_____

_____

_____

Could you send a copy of the above method(s) by first class mail? _____

Figure A-1 (Continued)

14. What specific type of equipment (e.g. broom sweeping, flushing, vacuuming) is used to clean up the abrasive/chemical residue from the roads after the storm? How soon is clean-up started after the storm? How often does the clean-up equipment operate over the same route after the storm?

	REMOVAL EQUIPMENT	TIME AFTER STORM	REMOVAL FREQUENCY
a. State Highways (rural areas):	_____	_____	_____
	_____	_____	_____
b. Expressways:	_____	_____	_____
	_____	_____	_____
c. City Streets:	_____	_____	_____
	_____	_____	_____
d. Major Intersections/Bridges:	_____	_____	_____
	_____	_____	_____
e. Other _____:	_____	_____	_____
	_____	_____	_____

15. Is the cleanliness of the road surface checked after post-storm (or spring) clean-up is completed? _____ If so, how is this performed? _____

_____

_____

16. Considering variations in storm frequency from year-to-year, do you believe that your annual use of abrasives/chemicals is rising, falling, or staying about the same? _____ If your consumption is falling, what specific practices have you used to minimize anti-skid material usage? _____

_____

_____

_____

_____

Figure A-1 (Continued)

OTHER COMMENTS

_____

_____

_____

_____

_____

_____

MATERIALS TO BE SENT TO MRI: _____

_____

_____

_____

Person Completing Questionnaire: _____ Date: _____

FOLLOW-UP CONVERSATION:

_____

_____

_____

_____

_____

_____

_____

_____

Person Performing Follow-Up: _____

Date of Follow-Up: _____

Figure A-1 (Concluded)

SD:DOT
Sanding Materials Questionaire

Agency: _____

(1) Check the types of materials used for Winter Operations Sanding:

_____ Pit Run Sand
_____ Screened Pit Run Sand
_____ Others (Specify) _____
_____ Crushed Pit Run Agg.
_____ Crushed Quarry Agg.

(2) Which of those checked provides the best skid resistance?

_____

(3) Provide specifications for material you purchase from commercial sources.

Sieve	% Passing
-	
-	
-	
-	
-	
-	

(4) Provide specifications for material you produce (crush/screen) with your own forces - If screening/crushing is not necessary, what is normal maximum particle size.

Sieve	% Passing
-	
-	
-	
-	
-	
-	

(5) Do you have a significant number of broken windshield complaints with the materials you use?

(6) If you use both natural (round) or crushed materials is there a difference in number of broken windshield complaints between the two? Yes. Complaints more common with which material? _____

(7) Do your specifications include requirements for Unit Weight? - No.

(8) Do your specifications for crushed pit run or quarry aggregate require a minimum percentage of fractured faces? No Minimum _____% Fracture on _____ face(s) for material retained on the _____ sieve.
(one-two-more) (sieve size)

Name: _____ Title: _____

Address: _____ Phone: _____

_____

Figure A-2. Sanding materials questionnaire.

APPENDIX B

BIBLIOGRAPHY

Tremayne, J. E. 1938. "Calcium Chloride Treatment of Abrasives Used in Ice Control," *Can. Engr.*, 75:8-10, November 15.

Schneider, T. R. 1952. "Snowdrifts and Winter Ice on Roads," NRC TT-1038, National Research Council of Canada, Ottawa, Technical Translation of original report from the Eidgenossissches Institut fur Schnee-und Lawinenforschung, *Interner Bericht NR. 302*, 141, 1959.

Highway Research Board. 1954. "Recommended Practice for Snow Removal and Treatment of Icy Pavements," *Current Road Problems*, No. 9, 3rd Rev., Dept. Maint., Comm. Snow and Ice Control, Highway Research Board, NAS-NRC, Washington, D.C.

Nichols, R. J., and W. I. J. Price. 1956. "Salt Treatment for Clearing Snow and Ice," *The Surveyor*, 115:886-888.

Wirshing, R. J. 1957. "Effect of Deicing Salts on Corrosion of Automobiles," *Bull. 150*, Highway Research Board, NAS-NRC, Washington, D.C.

Brohm, D. R, and H. R. Edwards. 1960. "Use of Chemicals and Abrasives in Snow and Ice Removal From Highways," *Res. Bull. 252*, Highway Research Board, NAS-NRC Publ. 761, Washington, D.C.

Webster, H. A. 1961. "Automobile Body Corrosion Problems," *Corrosion*, 17:8, 9-12.

Highway Research Board. 1962. "Current Practices for Highway Snow and Ice Control," *Current Road Problems*, No. 9, 4th Rev., Highway Research Board, NAS-NRC, Washington, D.C.

Himmelman, B. F. 1963. "Ice Removal on Highways and Outdoor Storage of Chloride Salts," *Highw. Res. Rec. 11*, Highway Research Board, NAS-NRC, Washington, D.C.

Solvay Technical and Engineering Service. 1963. *Calcium Chloride*, 3rd Edition, Bulletin No. 16.

Jorgensen, R., et al. 1964. "Nonchemical Methods of Snow and Ice Control on Highway Structures," Report No. 4, National Cooperative Highway Research Program, Highway Research Board, Washington, D.C.

Lang, C. H., and W. E. Dickinson. 1964. "Snow and Ice Control with Chemical Mixtures and Abrasives," *Highw. Res. Rec. 61*, Highway Research Board, NAS-NRC, Washington, D.C., pp. 14-18.

Fromm, H. J. 1967. "The Corrosion of Autobody Steel and the Effects on Inhibited Deicing Salts," *Rep. No. RR135*, Department of Highways, Toronto, Ontario.

National Research Council. 1967. "Manual on Snow Removal and Ice Control in Urban Areas," *Tech. Memo. No. 93, NRC 9904*, National Research Council of Canada, Ottawa, Ontario.

Minsk, D. L. 1968. "Electrically Conductive Asphalt for Control of Snow and Ice Accumulation," *Highw. Res. Rec., No. 227*, Highway Research Board, Washington, D.C., pp. 57-63.

Road Research Laboratory. 1968. "Salt Treatment of Snow and Ice on Roads," *Road Note No. 18*, Dept. Science and Industrial Research, 2nd Ed., Her Majesty's Stationery Off., London.

Dunnery, D. A. 1970. "Chemical Melting of Ice and Snow on Paved Surfaces," *Highway Research Board Special Reports No. 115*, 172-176.

Spellman, D. L., and R. F. Stratfull. 1970. "Chlorides and Bridge Deck Deterioration," *Highw. Res. Rec. 328*, Highway Research Board, NAS-NRC, Washington, D.C.

Byrd, Tallamy, et al. 1971. "Snow Removal and Ice Control Techniques at Interchanges," *Highw. Res. Rec. 127*, Highway Research Board, NAS-NRC, Washington, D.C.

Stewart, C. 1971. "Deterioration in Salted Bridge Decks," *Special Report 116*, Highway Research Board, NAS-NRC, Washington, D.C.

Struzeski, E. 1971. "Environmental Impact of Highway Deicing," Final Report 11040 GKK, U.S. Environmental Protection Agency, Edison, New Jersey, June.

Anon. 1973. "Recycled Winter Sand Tested in Connecticut," *Rural and Urban Roads*, 11:2, 51, February.

Murray, D. M., and M. R. Eigerman. 1973. "A Search: New Technology for Pavement Snow and Ice Control," EPA-R2-72-125, U.S. Environmental Protection Agency, Washington, D.C., December.

Richardson, D. L., et al. 1974. "Manual for Deicing Chemicals: Application Practices," EPA-670/2-74-045, National Environmental Research Center, U.S. Environmental Protection Agency, Cincinnati, Ohio, December.

NACE Group Committee T-3. 1975. "Deicing Salts, Their Use and Effects," *Matls. Perf.*, 14:9-14, April.

American Association of State Highway and Transportation Officials. 1976. "AASHTO Maintenance Manual," First Edition, AASHTO, Washington, D.C., February.

Welch, B. H., et al. 1976. "Economic Impact of Highway Snow and Ice Control--State-of-the-Art," Report No. FHWA-RD-7720, Federal Highway Administration, Offices of Research and Development, Washington, D.C.

McBride, J. C., et al. 1977. "Economic Impact of Highway Snow and Ice Control ESIC--User's Manual," Report No. FHWA-RD-77-96, Federal Highway Administration, Offices of Research and Development, Washington, D.C.

Dunn, S. A., and R. U. Schenk. 1979. "Alternative Highway Deicing Chemicals," in *Snow Control and Ice Control Research*, Special Report 185, Transportation Research Board, Washington, D.C.

Hu, A. C. 1979. "The Effect of Chloride Concentration on Automobile Stopping Distance," in *Snow Control and Ice Control Research*, Special Report 185, Transportation Research Board, Washington, D.C.

Dunn, S. A., and R. U. Schenk. 1980. "Alternate Highway Deicing Chemicals," FHWA-RD-79-108, Federal Highway Administration, Offices of Research and Development, Washington, D.C., March.

Baboian, R. 1981. "The Automotive Environment," in *Automotive Corrosion by Deicing Salts*, National Association of Corrosion Engineers, Houston, Texas.

Brown, M. G. 1981. "Corrosion of Highway Appurtenances Due to Deicing Salts," in *Automotive Corrosion by Deicing Salts*, National Association of Corrosion Engineers, Houston, Texas.

Cook, A. R. 1981. "Deicing Salts and the Longevity of Reinforced Concrete," in *Automotive Corrosion by Deicing Salts*, National Association of Corrosion Engineers, Houston, Texas.

Fromm, H. J. 1981. "Winter Maintenance Practice and Research in Ontario," in *Automotive Corrosion by Deicing Salts*, National Association of Corrosion Engineers, Houston, Texas.

Gray, D. M., and D. H. Male, Editors. 1981. *Handbook of Snow--Principles, Processes, Management, and Use*, Pergamon Press, New York.

McDonald, R. D. 1981. "Automotive Underbody Corrosion Testing," in *Automotive Corrosion by Deicing Salts*, National Association of Corrosion Engineers, Houston, Texas.

Passaglia, E., and R. A. Haines. 1981. "The National Cost of Automobile Corrosion," in *Automotive Corrosion by Deicing Salts*, National Association of Corrosion Engineers, Houston, Texas.

Wood, F. O. 1981. "Survey of Salt Use for Deicing Purposes," in *Automotive Corrosion by Deicing Salts*, National Association of Corrosion Engineers, Houston, Texas.

Minsk, D. L. 1982. "Optimizing Deicing Chemical Application Rates," CREEL Report 82-18, Federal Highway Administration, Washington, D.C., August.

Zaman, M. S., et al. 1982. "Prediction of Deterioration of Concrete Due to Freezing and Thawing and to Deicing Chemical Use," *American Concrete Institute Journal*, 79:1, 56-58, January-February.

Zaman, M. S., et al. 1982. "Prediction of Deterioration of Concrete Due to Freezing and Thawing and to Deicing Chemical Use," *American Concrete Institute Journal*, 6:502-504, November-December.

Eck, R. W., et al. 1983. "Evaluation of the Effect of Natural Brine Deicing Agents on Pavement Materials," *Transportation Research Record*, 933:24-31.

Huisman, C. L. 1983. "Cost Effective Roadway Deicing Using: Abrasives, Salt, and Calcium Chloride," Presented at Iowa Snow Conference, Ames, Iowa.

Connecticut Department of Transportation. 1984. "Snow and Ice Control Policy," State of Connecticut Bureau of Highways.

Anderson, R. W. 1985. "Safety Restoration During Snow Removal: Problems and Corrective Guidelines for Post Snow Storm Cleanup Operations," *Transafety Reporter*, 3:12, 4-5, December.

Saarela, A. 1985. "Future Views on Road Maintenance," *Tie ja Liikenne*, 55:8, 329-331.

Venermo, V., et al. 1985. "Katujen liukkaudentorjunta (Antiskid Treatment of Streets)," *Tie ja Liikenne*, 55:8, 332-335.

Eck, R. W., et al. 1987. "Natural Brine as an Additive to Abrasive Materials and Deicing Salts," *Transportation Research Record 1127*, 16-26.

Pitt, J. M., et al. 1987. "Sulfate Impurities From Deicing Salt and Durability of Portland Cement Mortar," *Transportation Research Record 1110*, 16-23.

Anonymous 1988. "Winter Maintenance--Learning Finland's Methods," *Better Roads*, 58:6, 22-26, June.

Hiatt, G. F. S., et al. 1988. "Calcium Magnesium Acetate: Comparative Toxicity Tests and an Industrial Hygiene Site Investigation," *Transportation Research Record 1157*, 20-26.

Jokinen, M. 1988. "Katupolun Vahentamista Tutkittu Turussa (Decreasing Street Dust Problems--A Study in Turku)," *Tie ja Liikenne*, 58:6, 22-24.

McElroy, A. D., et al. 1988. "Comparative Study of Chemical Deicers," *Transportation Research Record 1157*, 1-11.

McElroy, A. D., et al. 1988. "Study on Wetting Salt and Sand Stockpiles with Liquid Calcium Chloride," *Transportation Research Record 1157*, 38-43.

Nadezhdin, A., D. A. Mason, B. Malric, D. F. Lawless, and J. P. Fedosoff. 1988. "The Effect of Deicing Chemicals on Reinforced Concrete," *Transportation Research Record 1157*, 31-37.

Rainiero, J. M. 1988. "Investigation of the Ice-Retardant Characteristics of Verglimit-Modified Asphalt," *Transportation Research Record 1157*, 44-53.

Slick, D. S. 1988. "Effects of Calcium Magnesium Acetate on Pavements and Motor Vehicles," *Transportation Research Record 1157*, 27-30.

Anderson, R. C., and C. Auster. "Costs and Benefits of Road Salting," *Environ. Affairs*, 3:1, 129-144.

APPENDIX C

ALTERNATIVE SKID CONTROL MEASURES

ALTERNATIVE SKID CONTROL MEASURES[2]

Essentially all roadway ice and snow control measures in the United States consist of the long-established methods of plowing, sanding, and salting. Alternative measures to remove snow and ice from roadways have been extensively studied in the literature, particularly to identify methods that will reduce environmental damage resulting from the application of chloride salts. These alternative measures include other deicing chemicals as well as pavement coatings to prevent ice adhesion, resistance heating, mechanical ice removal methods, and new tire and vehicle design. The following sections describe studies of many of these alternative methods.

C.1 ALTERNATIVE MATERIALS

The Federal Highway Administration has conducted an extensive search (Dunn, 1980) to find road deicing chemicals to replace sodium chloride. Criteria for selection included a decrease in water solubility and freezing point, corrosivity, toxicity, relative cost (or cost potential), effect on soils, plants and water supplies, and flammability. The chemicals analyzed for deicing effectiveness consisted of both inorganic salts and organic compounds.

Inorganic salts (ionic compounds) are sodium-containing salts, salts containing chloride, nitrate or sulfate, sodium salts, carbonic and phosphoric acids, potassium salts of carbonic acid, potassium salts of phosphoric acid, tetrapotassium pyrophosphate, ammonium salts of phosphoric acid and ammonium salts of carbonic acid. Metal organic salts were also studied, as was glycine.

Nonionic deicers that were investigated by Dunn (1980) included methanol, ethanol and isopropanol, acetone, urea, formamide, dimethyl sulfoxide (DMSO) and ethyl carbamate (urethane). Two chemicals, calcium magnesium acetate (CMA) and methanol, were also field tested on a road, highway, sidewalk and parking ramp.

CMA and methanol were found to be as effective as sodium chloride, but without its drawbacks. Methanol reacts almost immediately to melt snow and ice, but is less persistent than sodium chloride. The eutectic temperature of methanol (−120°C or −184°F) is much lower than that of sodium chloride, and thus methanol works well at low ambient temperatures (i.e., below −7°C or 20°F) when the melting efficiency of sodium chloride diminishes.

The application of methanol to roadways would not create a source of particulate emissions, but would be a source of short term volatile organic compounds (VOCs) to persons applying the chemical because of its relatively high evaporation rate. For workers exposed to methanol vapors, the Occupational Safety and Health Administration has established an 8-h permissible exposure limit (PEL) of 200 ppm and a 15-min short

---

[2]References listed in Section 8 of main report.

term exposure limit (STEL) of 250 ppm. Also methanol can be absorbed by skin contact and has been found to be toxic to some animal species. This chemical is also very flammable during storage, but once applied to a road, will not ignite even when puddled on a snow covered road (Dunn, 1980).

The other candidate deicer, CMA, acts at about the same rate as sodium chloride in the temperature range of common activity and shows about the same persistence. However, CMA requires free water to be effective in melting snow and ice. CMA has other advantages:

1. Braking traction and skidding friction are about the same as NaCl.

2. Corrosion is retarded.

3. Soils are not affected.

4. Drinking water supplies are not harmed.

5. Unpurified CMA grains can be dark in color to enhance insolation and accelerate melting.

Dunn's study (1980) also reported that the acetate gradually decomposes to yield carbon dioxide and water, whereas the calcium and magnesium are reconverted to limestone, which would potentially be a source of fugitive particulate emissions. The unpurified CMA reaction product also contains calcium and magnesium carbonates (and some oxalates) as the insoluble impurities. However no data were found in the literature to indicate the particle sizes of these impurities or of the limestone residue of CMA. CMA is mildly basic, and some respiratory protection against dust would be desirable for workers handling the chemical.

Chollar (1984) noted that according to theoretical considerations, the weight ratio of CMA to sodium chloride to obtain equal deicing capabilities is 1.7 to 1.0. Because of the significantly higher cost of CMA compared to rock salt, Chollar foresaw future use of CMA only in certain areas, such as bridge decks, in urban areas of high traffic volume, and in areas of possible contamination of water supplies by sodium.

Table C-1 presents a summary of alternative deicing chemicals prepared by the Iowa Department of Transportation (1980). The Iowa report discussed advantages and disadvantages of each chemical based on effectiveness, cost, toxicity, and corrosiveness. Only five chemical alternatives are proposed, since Iowa stated that other alternative deicing chemicals had been tested and were not recommended because of "problems with safety, availability, economy and/or ecology." The nonrecommended chemicals included: ammonium acetate; ammonium nitrate; ammonium sulfate; alcohols; glycols; sodium formate or calcium formate; and ammonium carbamate.

TABLE C-1. ALTERNATIVE DEICING CHEMICALS (IOWA, 1980)

Alternative chemical	Advantages	Disadvantages and costs[a]
Formamide	Noncorrosive	Has higher freezing point
	Relatively nonslippery on pavement	10 to 15 times more costly
	Nontoxic unless biodegraded	
	Effective for use in automatic ice prevention systems	
Urea	Noncorrosive	Less effective
	Nonconductive	1½ to 2 times as much required for same effect
		5 to 10 times more costly
		Can be toxic
		Acceptable deicing chemical only above 15°F (–9°C)
		Runoff must be controlled, or only use in areas where runoff will not enter critical waterways
Tetrapotassium pyrophosphate (TKPP)	Toxicity no greater	Corrosive effect on vehicular steel
	Harmful, ecological effects no greater	15+ times as costly
Formamide-urea-water (75%) (20%) (5%) (liquid)	At very low temperatures outperforms salts	Costs 10+ times as much
	Considerably less corrosive	
	Nontoxic if not biodegraded	
	Effective for automatic ice prevention systems	
Tripotassium Phosphate-formamide (75%) (25%) (pellet)	Can be applied with existing equipment	Minor scaling of concrete may result
	Will melt ice at –10°F (–23.3°C)	May promote vegetation growth
	Effective at lower temperatures at reduced rate	Costs 10 to 15 times as much
	Corrosive effects acceptable	
	Nontoxic	

[a] Cost comparisons relative to rock salt.

The Iowa report also identified two pavement coating formulas to reduce the adherence of ice on pavements without compromising pavement skid resistance qualities. These included a modified traffic paint containing silicone rubber and a waterproofing compound combined with silicone rubber. Applications of these two pavement coatings were reported to have an estimated effective wear life of only one to two months on tested roads (150,000 to 300,000 vehicles passes). Another reported drawback is the release of flammable vapors into the atmosphere during application of these pavement coatings.

C.2 OTHER TECHNIQUES

According to Eck (1986), a properly designed snowplow can remove about 95% of a 2-in snowfall, with the remaining 5% removable with a small amount of rock salt. Seattle was reported to reduce chemical use by early plowing, under conditions of moderate to heavy snowfall (TRB, 1974). Wyoming (1984) also reported that wet snow usually requires immediate plowing and sanding, but dry snowfall should be allowed to build up to 1 to 2 in before plowing. Mechanical devices for snow/ice removal have been extensively studied as shown in Figure C-1 from Minsk (1981) and in Table C-2 from EPA (1972).

The Iowa Department of Transportation (1980) studied alternative deicing measures to reduce corrosion. These included bridge heating (including mobile thermal units), and application of ultrasonic (vibrational) and electromagnetic energy.

Wood (1983) also suggested a number of alternative methods to remove (or prevent the buildup of) snow and ice on roadways. These included electrically heated pavements, earth-heated pavements and geothermal heating, urethane foam and styrofoam insulation, air jet plows, infrared heat lamps and underbody-blade trucks. Rainiero (1988) and others have also investigated the use of pavement incorporating encapsulated pellets of calcium chloride. This material, referred to as Verglimit, has been tested in the United States, Canada, and Europe, with some success.

There have been a number of experiments with heated pavements, especially in England. According to EPA (1972), there are two types of road heaters: fluid circulating systems and electrical resistance heaters. Fluid circulating systems usually consist of pipes embedded in pavement that carry a heated, low-freezing point liquid. Pipes are closely spaced (about 1 to 1.5 ft apart) at the time the pavement is laid. Electrical pavement heaters include high voltage, insulated cable systems; low voltage systems using uninsulated metal mesh; and electrically conductive pavements.

Other alternative approaches have entailed the use of vibrational and electromagnetic energy. Both methods are very inefficient because the energy requirements are too great.

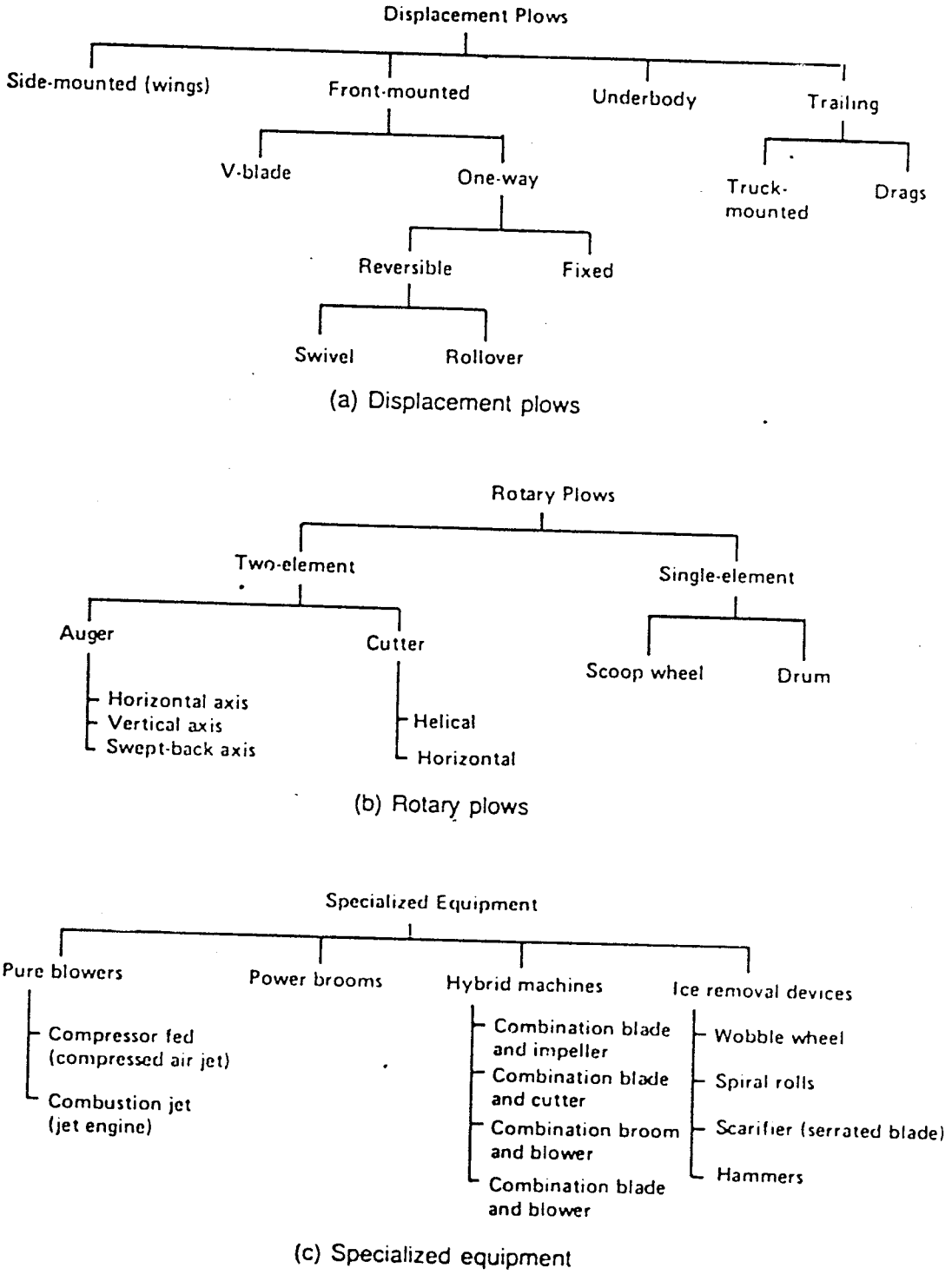


Figure C-1. Family tree of snow removal equipment (Minsk, 1981).

TABLE C-2. MECHANICAL DEVICES FOR SNOW REMOVAL AND ICE CONTROL (EPA, 1972)

1. Blade or displacement plows
   - 1.1 Front-mounted
     - One-way blade
       - Fixed position (right or left cast)
       - Reversible (swivel or roll-over)
       - V-blade
   - 1.2 Underbody
     - Road grader
     - Truck-mounted
   - 1.3 Side-mounted (wings)
   - 1.4 Trailing

2. Rotary snow blowers
   - 2.1 Two-element (impeller)
     - Auger
       - Horizontal axis
       - Vertical axis
       - Swept-back axis
     - Cutters
       - Helical
       - Horizontal breakers (rakes)
   - 2.2 Single-element (no impeller)
     - Scoop wheel
     - Drum

3. Pure blowers
   - 3.1 Compressed air jet (compressor-fed)
   - 3.2 Combustion jet (jet engine)

4. Power brooms (rotary brush)

5. Specialized ice removing equipment
   - 5.1 Ice crushing rollers (pressure cutting edges)
     - Wobble wheel
     - Spiral rolls
     - Serrated blade
   - 5.2 Ice melting machines

6. Combination equipment
   - 6.1 Blade and impeller
   - 6.2 Blade and cutter
   - 6.3 Blade and compressed air
   - 6.4 Broom and blower
   - 6.5 Burner and blower
   - 6.6 Burner, broom, and vacuum

A comprehensive study led by Blackburn (1978) produced the document, "Physical Alternatives to Chemicals for Highway Deicing." This U.S. Department of Transportation document reported on practical and economical alternative means of highway deicing. Twenty-one deicing concepts were identified and evaluated for their potential usefulness. The selection of concepts was guided by a consideration of three separate steps that are generally required of any successful method to remove snow and ice from roadways:

1. Prevent, reduce, or eliminate the bond between the pavement and the ice/snow.

2. Break and dislodge the ice/snow.

3. Remove the ice/snow fragments from the traveled way.

A rating scheme was developed by Blackburn (1978) to compare the different physical alternatives to deicing chemicals and to select the most feasible methods for further study. A five-category rating scheme was used:

1. Technical feasibility.

2. Operational feasibility--maintenance operations.

3. Operational feasibility--traffic operations and safety.

4. Economic acceptability.

5. Environmental acceptability.

This rating scheme was applied to the identified alternative physical deicing methods and the results are summarized in Table C-3. Unadjusted, or raw, ratings "are the best available measures of the feasibility/acceptability of a concept, based on the rating for each category, arrived at upon objective consideration of many factors." Adjusted ratings incorporate a measure of uncertainty to include the reliability (or certainty) of the ratings. A rating of 10 is best, whereas a rating of 0 is the least desirable rating.

About 75% of the investigated alternatives have low ratings resulting from excessive power requirements, size and bulk of the equipment required, low efficiency, high costs, safety factors, and potential damage to the environment (including pavement). Unadjusted overall ratings of less than 5.5 identify concepts considered unacceptable. Four candidate concepts had ratings between 5.5 and 6.0 and were noted as deserving additional consideration. These included release agents in the surface course (e.g., Verglimit-modified asphalt), mechanical waves (ultrasonics), rotary blowers, and plow blades with air jets.

TABLE C-3. RATING OF CONCEPTS FOR ALTERNATIVE PHYSICAL DEICING METHODS (BLACKBURN, 1978)

	Concept	Category rating values[a]											
		Technical feasibility		Operational feasibility maintenance operations		Operational feasibility traffic operations and safety		Economic acceptability		Environmental acceptability		Overall rating values[a] (average)	
Step 1:	Prevention, reduction, or elimination of adhesive bond of ice to pavement												
	• Release agents on pavement surface	9.25	7.45	6.82	3.90	3.67	1.78	6.16	0.66	8.40	3.40	6.86	3.44
	• Gas releasing agents in surface course	8.00	4.23	6.56	3.16	4.33	0.43	7.48	0.76	7.60	1.48	6.79	2.01
	• Release agents in surface course	6.50	3.88	6.21	3.16	3.67	0.56	6.16	0.75	7.20	2.64	5.95	2.20
	• Temporary melting at interface with energy delivered by:												
	—Current in surface course	3.75	2.38	5.57	1.82	4.33	0.83	4.78	0.48	8.80	0.88	5.45	1.28
	—Visual range electromagnetic radiation	3.50	1.05	5.24	0.52	4.33	0.43	4.15	0.41	6.80	0.68	4.80	0.62
	—Microwave electromagnetic radiation	3.00	0.96	4.92	0.57	4.33	0.43	3.73	0.37	6.80	0.68	4.56	0.60
	—Induced current at the interface	2.50	0.48	4.68	0.48	4.33	0.43	4.90	0.49	6.40	0.64	4.56	0.50
	—Induced current in surface course	2.50	0.58	4.68	0.48	4.33	0.43	4.69	0.61	6.40	0.64	4.52	0.55
	• Gas formation at the interface by electrolysis	2.50	0.26	6.10	0.63	4.33	0.43	4.99	0.50	8.80	0.88	5.34	0.54
Step 2:	Breaking and dislodging of the ice/snow layer												
	• Mechanical devices producing steady or impact stresses	8.25	6.08	5.71	2.61	5.56	3.69	4.46	0.44	7.20	0.72	6.24	2.71
	• Mechanical waves (ultrasonic)	5.25	1.13	5.86	0.65	7.74	0.77	2.67	0.26	6.80	0.68	5.66	0.70
	• Stresses under tire passages	5.50	1.05	5.23	1.65	3.54	1.58	7.07	0.72	6.00	2.40	5.47	1.48
	• Variable electromagnetic fields	3.00	0.36	4.63	0.47	6.76	0.67	1.78	0.18	6.80	0.68	4.59	0.47

(continued)

TABLE C-3 (continued)

Concept	Category rating values[a]											
	Technical feasibility		Operational feasibility maintenance operations		Operational feasibility traffic operations and safety		Economic acceptability		Environmental acceptability		Overall rating values[a] (average)	
• Gas formations by electrolysis at ice/snow-to-pavement interface	2.75	0.43	4.35	0.45	6.76	0.67	1.78	0.18	6.80	0.68	4.49	0.48
• Heated plow blades	3.00	0.36	3.91	0.53	5.74	0.91	1.89	0.21	6.80	0.68	4.27	0.54
• Jets of gas or liquids driven by compressors and pumps	3.00	0.46	3.48	0.43	4.30	0.87	2.68	0.27	5.60	0.56	3.81	0.52
Step 3: Removal of the ice/snow from the traveled way												
• Blade action	9.50	9.05	5.58	4.20	5.18	3.99	6.74	5.52	7.60	7.60	6.92	6.07
• Rotary blowers	7.50	7.25	5.25	4.59	5.74	4.59	3.48	2.48	7.20	7.20	5.83	5.22
• Plow blades with air jets	7.00	3.30	5.58	0.87	4.64	0.93	4.89	0.49	6.20	0.62	5.66	1.24
• Traffic action	5.50	1.05	5.23	1.65	3.54	1.58	7.07	0.72	6.00	2.40	5.47	1.48
• Sweeper action	5.50	4.70	4.92	3.44	5.56	3.34	4.53	1.50	6.40	4.12	5.38	3.42

[a] Numbers appearing in left column of each category are unadjusted rating values; adjusted rating values appear in right column of each category.

Four closely related concepts had unadjusted ratings above 6 and were evaluated as the most promising alternative deicing methods: release agents on the pavement surface, gas-releasing agents in the surface course, mechanical deicing methods producing steady or impact stresses, and blade action.

One of the most promising concepts was actually tested by Blackburn (1978)—mechanical devices (rotating metal discs) that put steady stresses on the ice/snow pavement bond. Various disc configurations, an array of two discs, and a simulated plow blade were laboratory tested. Results from these tests were mixed, but suggested that ice was difficult to remove completely by mechanical devices producing steady stresses. The adhesive bond of ice to some materials can exceed the cohesive strength in the ice itself, and may be supplemented by mechanical interlocking to pavement surface asperities. Discs need to penetrate through to the ice-pavement interface, but disc depth proved difficult to control. This problem could possibly cause more than superficial pavement damage by field equipment.

C.3 CONCLUSIONS

Of the alterative deicers identified above, only CMA shows some limited potential for applications such as bridges, intersections,and the like. For this reason, CMA was compared to two common deicers (rock salt and $CaC1_2$) in small scale experiments. The results of these experiments can be found in Section 6.3.3 of the main text.

With regard to other alternative methods of ice and snow control, new techniques for mechanical ice disbonding appears to be the most promising. An evaluation of these techniques was beyond the scope of this particular study and thus were not evaluated.

APPENDIX D

ASTM SILT ANALYSIS METHODS

Designation: C 117 – 87

Standard Test Method for Materials Finer than 75-μm (No. 200) Sieve in Mineral Aggregates by Washing[1]

This standard is issued under the fixed designation C 117; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This test method has been approved for use by agencies of the Department of Defense and for listing in the DoD Index of Specifications and Standards.

1. Scope

1.1 This test method covers determination of the amount of material finer than a 75-μm (No. 200) sieve in aggregate by washing. Clay particles and other aggregate particles that are dispersed by the wash water, as well as water-soluble materials, will be removed from the aggregate during the test.

1.2 Two procedures are included, one using only water for the washing operation, and the other including a wetting agent to assist the loosening of the material finer than the 75-μm (No. 200) sieve from the coarser material. Unless otherwise specified, Procedure A (water only) shall be used.

1.3 The values stated in acceptable metric units are to be regarded as the standard.

1.4 *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

C 136 Method for Sieve Analysis of Fine and Coarse Aggregates[2]

C 670 Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials[2]

C 702 Practice for Reducing Field Samples of Aggregate to Testing Size[2]

D 75 Practice for Sampling Aggregates[3]

E 11 Specification for Wire-Cloth Sieves for Testing Purposes[4]

2.2 *AASHTO Standard:*

T 11 Method of Test for Amount of Material Finer than 0.075-mm Sieve in Aggregate[5]

3. Summary of Method

3.1 A sample of the aggregate is washed in a prescribed manner, using either plain water or water containing a wetting agent, as specified. The decanted wash water, containing suspended and dissolved material, is passed through a 75-μm (No. 200) sieve. The loss in mass resulting from the wash treatment is calculated as mass percent of the original sample and is reported as the percentage of material finer than a 75-μm (No. 200) sieve by washing.

4. Significance and Use

4.1 Material finer than the 75-μm (No. 200) sieve can be separated from larger particles much more efficiently and completely by wet sieving than through the use of dry sieving. Therefore, when accurate determinations of material finer than 75 μm in fine or coarse aggregate are desired, this test method is used on the sample prior to dry sieving in accordance with Method C 136. The results of this test method are included in the calculation in Method C 136, and the total amount of material finer than 75 μm by washing, plus that obtained by dry sieving the same sample, is reported with the results of Method C 136. Usually the additional amount of material finer than 75 μm obtained in the dry sieving process is a small amount. If it is large, the efficiency of the washing operation should be checked. It could, also, be an indication of degradation of the aggregate.

4.2 Plain water is adequate to separate the material finer than 75 μm from the coarser material with most aggregates. In some cases, the finer material is adhering to the larger particles, such as some clay coatings and coatings on aggregates that have been extracted from bituminous mixtures. In these cases, the fine material will be separated more readily with a wetting agent in the water.

5. Apparatus and Materials

5.1 *Balance*—A balance or scale readable and accurate to 0.1 g or 0.1 % of the test load, whichever is greater, at any point within the range of use.

5.2 *Sieves*—A nest of two sieves, the lower being a 75-μm (No. 200) sieve and the upper a 1.18-mm (No. 16) sieve, both conforming to the requirements of Specification E 11.

5.3 *Container*—A pan or vessel of a size sufficient to contain the sample covered with water and to permit vigorous agitation without loss of any part of the sample or water.

5.4 *Oven*—An oven of sufficient size, capable of maintaining a uniform temperature of 110 ± 5°C (230 ± 9°F).

---

[1] This test method is under the jurisdiction of ASTM Committee C-9 on Concrete and Concrete Aggregates and is the direct responsibility of Subcommittee C 09.03.05 on Methods of Testing and Specifications for Physical Characteristics of Concrete Aggregates.

Current edition approved Feb. 9, 1987. Published March 1987. Originally published as C 117 – 35 T. Last previous edition C 117 – 84.

An alternative procedure that allows the use of a wetting agent was added to the current edition of this test method.

[2] *Annual Book of ASTM Standards*, Vol 04.02.

[3] *Annual Book of ASTM Standards*, Vols 04.02 and 04.03.

[4] *Annual Book of ASTM Standards*, Vols 04.02 and 14.02.

[5] Available from the American Association of State Highway and Transportation Officials, 444 N. Capitol St., NW, Suite 225, Washington, DC 20001.

5.5 *Wetting Agent*—Any dispersing agent, such as liquid dishwashing detergents, that will promote separation of the fine materials.

NOTE 1—The use of a mechanical apparatus to perform the washing operation is not precluded, provided the results are consistent with those obtained using manual operations. The use of some mechanical washing equipment with some samples may cause degradation of the sample.

6. Sampling

6.1 Sample the aggregate in accordance with Practice D 75. If the same test sample is to be tested for sieve analysis according to Method C 136, comply with the applicable requirements of that method.

6.2 Thoroughly mix the sample of aggregate to be tested and reduce the quantity to an amount suitable for testing using the applicable methods described in Methods C 702. If the same test sample is to be tested according to Method C 136, the minimum mass shall be as described in the applicable sections of that method. Otherwise, the mass of the test sample, after drying, shall conform with the following:

Nominal Maximum Size	Minimum Mass, g
2.36 mm (No. 8)	100
4.75 mm (No. 4)	500
9.5 mm (⅜ in.)	1000
19.0 mm (¾ in.)	2500
37.5 mm (1½ in.) or larger	5000

The test sample shall be the end result of the reduction. Reduction to an exact predetermined mass shall not be permitted.

7. Selection of Procedure

7.1 Procedure A shall be used, unless otherwise specified by the Specification with which the test results are to be compared, or when directed by the agency for which the work is performed.

8. Procedure A—Washing with Plain Water

8.1 Dry the test sample to constant mass at a temperature of 110 ± 5°C (230 ± 9°F). Determine the mass to the nearest 0.1 % of the mass of the test sample.

8.2 If the applicable specification requires that the amount passing the 75-µm (No. 200) sieve shall be determined on a portion of the sample passing a sieve smaller than the nominal maximum size of the aggregate, separate the sample on the designated sieve and determine the mass of the material passing the designated sieve to 0.1 % of the mass of this portion of the test sample. Use this mass as the original dry mass of the test sample in 10.1.

NOTE 2—Some specifications for aggregates with a nominal maximum size of 50 mm or greater, for example, provide a limit for material passing the 75-µm (No. 200) sieve determined on that portion of the sample passing the 25.0-mm sieve. Such procedures are necessary since it is impractical to wash samples of the size required when the same test sample is to be used for sieve analysis by Method C 136.

8.3 After drying and determining the mass, place the test sample in the container and add sufficient water to cover it. No detergent, dispersing agent, or other substance shall be added to the water. Agitate the sample with sufficient vigor to result in complete separation of all particles finer than the 75-µm (No. 200) sieve from the coarser particles, and to bring the fine material into suspension. Immediately pour the wash water containing the suspended and dissolved soli over the nested sieves, arranged with the coarser sieve on to Take care to avoid, as much as feasible, the decantation coarser particles of the sample.

8.4 Add a second charge of water to the sample in tl container, agitate, and decant as before. Repeat this oper tion until the wash water is clear.

NOTE 3—If mechanical washing equipment is used, the charging water, agitating, and decanting may be a continuous operation.

8.5 Return all material retained on the nested sieves t flushing to the washed sample. Dry the washed aggregate constant mass at a temperature of 110 ± 5°C (230 ± 9°F) ar determine the mass to the nearest 0.1 % of the original ma of the sample.

9. Procedure B—Washing Using a Wetting Agent

9.1 Prepare the sample in the same manner as f Procedure A.

9.2 After drying and determining the mass, place the te sample in the container. Add sufficient water to cover tl sample, and add wetting agent to the water (Note 4). Agita the sample with sufficient vigor to result in complete sep ration of all particles finer than the 75-µm (No. 200) sie from the coarser particles, and to bring the fine material in suspension. Immediately pour the wash water containing tl suspended and dissolved solids over the nested sieve arranged with the coarser sieve on top. Take care to avoid, much as feasible, the decantation of coarser particles of tl sample.

NOTE 4—These should be enough wetting agent to produce a sm amount of suds when the sample is agitated. The quantity will deper on the hardness of the water and the quality of the detergent. Excessi suds may overflow the sieves and carry some material with them.

9.3 Add a second charge of water (without wetting agen to the sample in the container, agitate, and decant as befor Repeat this operation until the wash water is clear.

9.4 Complete the test as for Procedure A.

10. Calculation

10.1 Calculate the amount of material passing a 75-µ (No. 200) sieve by washing as follows:

$$A = [(B - C)/B] \times 100$$

where:

A = percentage of material finer than a 75-µm (No. 20 sieve by washing,
B = original dry mass of sample, g, and
C = dry mass of sample after washing, g.

11. Report

11.1 Report the percentage of material finer than tl 75-µm (No. 200) sieve by washing to the nearest 0.1 except if the result is 10 % or more, report the percentage the nearest whole number.

11.2 Include a statement as to which procedure was use

12. Precision and Bias

12.1 The estimates of precision of this test method liste in Table 1 are based on results from the AASHTO Materia Reference Laboratory Reference Sample Program, wi testing conducted by this test method and AASHTO Metho

TABLE 1 Precision

	Standard Deviation (IS)[A], %	Acceptable Range of two Results (D2S)[A], %
Coarse Aggregate[B]		
Single-Operator Precision	0.10	0.28
Multilaboratory Precision	0.22	0.62
Fine Aggregate[C]		
Single-Operator Precision	0.15	0.43
Multilaboratory Precision	0.29	0.82

[A] These numbers represent the (IS) and (D2S) limits as described in Practice C 670.

[B] Precision estimates are based on aggregates having a nominal maximum size of 19.0 mm (¾ in.) with less than 1.5% finer than the 75-µm (No. 200) sieve.

[C] Precision estimates are based on fine aggregates having 1.0 to 3.0% finer than the 75-µm (No. 200) sieve.

T 11. The significant differences between the methods at the ime the data were acquired is that Method T 11 required, ınd Method C 117 prohibited, the use of a wetting agent. The data are based on the analyses of more than 100 paired test results from 40 to 100 laboratories.

12.2 *Bias*—Since there is no accepted reference material suitable for determining the bias for the procedure in this test method, no statement on bias is made.

The American Society for Testing and Materials takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, 1916 Race St., Philadelphia, PA 19103.

Standard Method for Sieve Analysis of Fine and Coarse Aggregates[1]

This standard is issued under the fixed designation C 136; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This method has been approved for use by agencies of the Department of Defense and for listing in the DoD Index of Specifications and Standards.

1. Scope

1.1 This method covers the determination of the particle size distribution of fine and coarse aggregates by sieving.

1.2 Some specifications for aggregates which reference this method contain grading requirements including both coarse and fine fractions. Instructions are included for sieve analysis of such aggregates.

1.3 The values stated in acceptable metric units (SI units and units specifically approved in ASTM E 380 for use with SI units) are to be regarded as the standard. The values in parentheses are provided for information purposes only.

1.4 *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of whoever uses this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

C 117 Test Method for Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing[2]

C 670 Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials[2]

C 702 Practice for Reducing Field Samples of Aggregate to Testing Size[3]

D 75 Practice for Sampling Aggregates[2]

E 11 Specification for Wire-Cloth Sieves for Testing Purposes[2]

E 380 Metric Practice[4]

2.2 *AASHTO Standard:*

AASHTO No. T 27 Sieve Analysis of Fine and Coarse Aggregates[5]

3. Summary of Method

3.1 A weighed sample of dry aggregate is separated through a series of sieves of progressively smaller openings for determination of particle size distribution.

4. Significance and Use

4.1 This method is used primarily to determine the grading of materials proposed for use as aggregates or being used as aggregates. The results are used to determine compliance of the particle size distribution with applicable specification requirements and to provide necessary data for control of the production of various aggregate products and mixtures containing aggregates. The data may also be useful in developing relationships concerning porosity and packing.

4.2 Accurate determination of material finer than the 75-µm (No. 200) sieve cannot be achieved by use of this method alone. Test Method C 117 for material finer than 75-µm sieve by washing should be employed.

5. Apparatus

5.1 *Balances*—Balances or scales used in testing fine and coarse aggregate shall have readability and accuracy as follows:

5.1.1 For fine aggregate, readable to 0.1 g and accurate to 0.1 g or 0.1 % of the test load, whichever is greater, at any point within the range of use.

5.1.2 For coarse aggregate, or mixtures of fine and coarse aggregate, readable and accurate to 0.5 g or 0.1 % of the test load, whichever is greater, at any point within the range of use.

5.2 *Sieves*—The sieves shall be mounted on substantial frames constructed in a manner that will prevent loss of material during sieving. The sieves shall conform to Specification E 11. Sieves with openings larger than 125 mm (5 in.) shall have a permissible variation in average opening of ±2 % and shall have a nominal wire diameter of 8.0 mm (5/16 in.) or larger.

NOTE 1—It is recommended that sieves mounted in frames larger than standard 203-mm (8 in.) diameter frames be used for testing coarse aggregate.

5.3 *Mechanical Sieve Shaker*—A mechanical sieve shaker, if used, shall impart a vertical, or lateral and vertical, motion to the sieve, causing the particles thereon to bounce and turn so as to present different orientations to the sieving surface. The sieving action shall be such that the criterion for adequacy of sieving described in 7.4 is met in a reasonable time period.

NOTE 2—Use of a mechanical sieve shaker is recommended when the size of the sample is 20 kg or greater, and may be used for smaller samples, including fine aggregate. Excessive time (more than approximately 10 min) to achieve adequate sieving may result in degradation of the sample. The same mechanical sieve shaker may not be practical for

[1] This method is under the jurisdiction of ASTM Committee C-9 on Concrete and Concrete Aggregates and is the direct responsibility of Subcommittee C09.03.05 on Methods of Testing and Specifications for Physical Characteristics of Concrete Aggregates.

Current edition approved Oct. 26, 1984. Published December 1984. Originally published as C 136 – 38 T. Last previous edition C 136 – 83.

[2] *Annual Book of ASTM Standards*, Vols 04.02 and 04.03.

[3] *Annual Book of ASTM Standards*, Vol 04.02.

[4] *Annual Book of ASTM Standards*, Vol 14.02. Excerpts in all volumes.

[5] Available from American Association of State Highway and Transportation Officials, 444 North Capitol St. N.W., Suite 225, Washington, DC 20001.

all sizes of samples, since the large sieving area needed for practical sieving of a large nominal size coarse aggregate very likely could result in loss of a portion of the sample if used for a small sample of coarse aggregate or fine aggregate.

5.4 *Oven*—An oven of appropriate size capable of maintaining a uniform temperature of 110 ± 5°C (230 ± 9°F).

6. Sampling

6.1 Sample the aggregate in accordance with Practice D 75. The weight of the field sample shall be the weight shown in Practice D 75 or four times the weight required in 6.4 and 6.5 (except as modified in 6.6), whichever is greater.

6.2 Thoroughly mix the sample and reduce it to an amount suitable for testing using the applicable procedures described in Methods C 702. The sample for test shall be approximately of the weight desired when dry and shall be the end result of the reduction. Reduction to an exact predetermined weight shall not be permitted.

NOTE 3—Where sieve analysis, including determination of material finer than the 75-µm sieve, is the only testing proposed, the size of the sample may be reduced in the field to avoid shipping excessive quantities of extra material to the laboratory.

6.3 *Fine Aggregate*—The test sample of fine aggregate shall weigh, after drying, approximately the following amount:

Aggregate with at least 95 % passing a 2.36-mm (No. 8) sieve	100 g
Aggregate with at least 85 % passing a 4.75-mm (No. 4) sieve and more than 5 % retained on a 2.36-mm (No. 8) sieve	500 g

6.4 *Coarse Aggregate*—The weight of the test sample of coarse aggregate shall conform with the following:

Nominal Maximum Size, Square Openings, mm (in.)	Minimum Weight of Test Sample, kg (lb)
9.5 (3/8)	1 (2)
12.5 (1/2)	2 (4)
19.0 (3/4)	5 (11)
25.0 (1)	10 (22)
37.5 (1 1/2)	15 (33)
50 (2)	20 (44)
63 (2 1/2)	35 (77)
75 (3)	60 (130)
90 (3 1/2)	100 (220)
100 (4)	150 (330)
112 (4 1/2)	200 (440)
125 (5)	300 (660)
150 (6)	500 (1100)

6.5 *Coarse and Fine Aggregate Mixtures*—The weight of the test sample of coarse and fine aggregate mixtures shall be the same as for coarse aggregate in 6.4.

6.6 The size of sample required for aggregates with large nominal maximum size is such as to preclude testing except with large mechanical sieve shakers. However, the intent of this method will be satisfied for samples of aggregate larger than 50 mm nominal maximum size if a smaller weight of sample is used, provided that the criterion for acceptance or rejection of the material is based on the average of results of several samples, such that the sample size used times the number of samples averaged equals the minimum weight of sample shown in 6.4.

6.7 In the event that the amount of material finer than the 75-µm (No. 200) sieve is to be determined by Test Method C 117, proceed as follows:

6.7.1 For aggregates with a nominal maximum size of 12.5 mm (1/2 in.) or less, use the same test sample for testing by Test Method C 117 and this method. First test the sample in accordance with Test Method C 117 through the final drying operation, then dry sieve the sample as stipulated in 7.2 through 7.7 of this method.

6.7.2 For aggregates with a nominal maximum size greater than 12.5 mm (1/2 in.), a single test sample may be used as described in 6.7.1, or separate test samples may be used for Test Method C 117 and this method.

6.7.3 Where the specifications require determination of the total amount of material finer than the 75-µm sieve by washing and dry sieving, use the procedure described in 6.7.1.

7. Procedure

7.1 Dry the sample to constant weight at a temperature of 110 ± 5°C (230 ± 9°F).

NOTE 4—For control purposes, particularly where rapid results are desired, it is generally not necessary to dry coarse aggregate for the sieve analysis test. The results are little affected by the moisture content unless: (*1*) the nominal maximum size is smaller than about 12.5 mm (1/2 in.); (*2*) the coarse aggregate contains appreciable material finer than 4.75 mm (No. 4); or (*3*) the coarse aggregate is highly absorptive (a lightweight aggregate, for example). Also, samples may be dried at the higher temperatures associated with the use of hot plates without affecting results, provided steam escapes without generating pressures sufficient to fracture the particles, and temperatures are not so great as to cause chemical breakdown of the aggregate.

7.2 Suitable sieve sizes shall be selected to furnish the information required by the specifications covering the material to be tested. The use of additional sieves may be desirable to provide other information, such as fineness modulus, or to regulate the amount of material on a sieve. Nest the sieves in order of decreasing size of opening from top to bottom and place the sample on the top sieve. Agitate the sieves by hand or by mechanical apparatus for a sufficient period, established by trial or checked by measurement on the actual test sample, to meet the criterion for adequacy or sieving described in 7.4.

7.3 Limit the quantity of material on a given sieve so that all particles have opportunity to reach sieve openings a number of times during the sieving operation. For sieves with openings smaller than 4.75-mm (No. 4), the weight retained on any sieve at the completion of the sieving operation shall not exceed 6 kg/m^2 (4 g/in.^{2}) of sieving surface. For sieves with openings 4.75 mm (No. 4) and larger, the weight in kg/m^2 of sieving surface shall not exceed the product of 2.5 × (sieve opening in mm). In no case shall the weight be so great as to cause permanent deformation of the sieve cloth.

NOTE 5—The 6 kg/m^2 amounts to 194 g for the usual 203-mm (8 in.) diameter sieve. The amount of material retained on a sieve may be regulated by (*1*) the introduction of a sieve with larger openings immediately above the given sieve or (*2*) testing the sample in a number of increments.

7.4 Continue sieving for a sufficient period and in such manner that, after completion, not more than 1 weight % of the residue on any individual sieve will pass that sieve during 1 min of continuous hand sieving performed as follows: Hold the individual sieve, provided with a snug-fitting pan and cover, in a slightly inclined position in one hand. Strike the side of the sieve sharply and with an upward motion against the heel of the other hand at the rate of about 150

times per minute, turn the sieve about one sixth of a revolution at intervals of about 25 strokes. In determining sufficiency of sieving for sizes larger than the 4.75-mm (No. 4) sieve, limit the material on the sieve to a single layer of particles. If the size of the mounted testing sieves makes the described sieving motion impractical, use 203-mm (8 in.) diameter sieves to verify the sufficiency of sieving.

7.5 In the case of coarse and fine aggregate mixtures, the portion of the sample finer than the 4.75-mm (No. 4) sieve may be distributed among two or more sets of sieves to prevent overloading of individual sieves.

7.5.1 Alternatively, the portion finer than the 4.75-mm (No. 4) sieve may be reduced in size using a mechanical splitter according to Methods C 702. If this procedure is followed, compute the weight of each size increment of the original sample as follows:

$$A = \frac{W_1}{W_2} \times B$$

where:

A = weight of size increment on total sample basis,
W_1 = weight of fraction finer than 4.75-mm (No. 4) sieve in total sample,
W_2 = weight of reduced portion of material finer than 4.75-mm (No. 4) sieve actually sieved, and
B = weight of size increment in reduced portion sieved.

7.6 Unless a mechanical sieve shaker is used, hand sieve particles larger than 75 mm (3 in.) by determining the smallest sieve opening through which each particle will pass. Start the test on the smallest sieve to be used. Rotate the particles, if necessary, in order to determine whether they will pass through a particular opening; however, do not force particles to pass through an opening.

7.7 Determine the weight of each size increment by weighing on a scale or balance conforming to the requirements specified in 5.1 to the nearest 0.1 % of the total original dry sample weight. The total weight of the material after sieving should check closely with original weight of sample placed on the sieves. If the amounts differ by more than 0.3 %, based on the original dry sample weight, the results should not be used for acceptance purposes.

7.8 If the sample has previously been tested by Test Method C 117, add the weight finer than the 75-µm (No. 200) sieve determined by that method to the weight passing the 75-µm (No. 200) sieve by dry sieving of the same sample in this method.

8. Calculation

8.1 Calculate percentages passing, total percentages retained, or percentages in various size fractions to the nearest 0.1 % on the basis of the total weight of the initial dry sample. If the same test sample was first tested by Test Method C 117, include the weight of material finer than the 75-µm (No. 200) size by washing in the sieve analysis calculation; and use the total dry sample weight prior to washing in Test Method C 117 as the basis for calculating all the percentages.

8.2 Calculate the fineness modulus, when required, by adding the total percentages of material in the sample that is coarser than each of the following sieves (cumulative percentages retained), and dividing the sum by 100: 150-µm (No. 100), 300-µm (No. 50), 600-µm (No. 30), 1.18-mm (No. 16), 2.36-mm (No. 8), 4.75-mm (No. 4), 9.5-mm (3/8-in.), 19.0-mm (3/4-in.), 37.5-mm (1½-in.), and larger, increasing in the ratio of 2 to 1.

9. Report

9.1 Depending upon the form of the specifications for use of the material under test, the report shall include the following:

9.1.1 Total percentage of material passing each sieve, or

9.1.2 Total percentage of material retained on each sieve, or

9.1.3 Percentage of material retained between consecutive sieves.

9.2 Report percentages to the nearest whole number, except if the percentage passing the 75-µm (No. 200) sieve is less than 10 %, it shall be reported to the nearest 0.1 %.

9.3 Report the fineness modulus, when required, to the nearest 0.01.

10. Precision

10.1 The estimates of precision of this method listed in Table 1 are based on results from the AASHTO Materials Reference Laboratory Reference Sample Program, with testing conducted by this method and AASHTO Method T 27. While there are differences in the minimum weight of the test sample required for other nominal maximum sizes of aggregate, no differences entered into the testing to affect the determination of these precision indices. The data are based on the analyses of more than 100 paired test results from 40 to 100 laboratories. The values in the table are given for different ranges of percentage of aggregate passing one sieve and retained on the next finer sieve.

TABLE 1 Precision

	% of Size Fraction Between Consecutive Sieves	Coefficient of Variation (1S %), %[B]	Standard Deviation (1S), %[A]	Acceptable Range of Test Results	
				(D2S %)[B] % of Avg.	(D2S),[A] %
Coarse Aggregates:[C]					
Single-Operator Precision	0 to 3	30[D]	...	85[D]	...
	3 to 10		1.4[D]		4.0[D]
	10 to 20		0.95		2.7
	20 to 50		1.38		3.9
Multilaboratory Precision	0 to 3	35[D]	...	99[D]	...
	3 to 10		1.06		3.0
	10 to 20		1.66		4.7
	20 to 30		2.01		5.7
	30 to 40		2.44		6.9
	40 to 50		3.18		9.0
Fine Aggregates:					
Single-Operator Precision	0 to 3		0.14		0.4
	3 to 10		0.43		1.2
	10 to 20		0.60		1.7
	20 to 30		0.64		1.8
	30 to 40		0.71		2.0
	40 to 50		...		...
Multilaboratory Precision	0 to 3		0.21		0.6
	3 to 10		0.57		1.6
	10 to 20		0.95		2.7
	20 to 30		1.24		3.5
	30 to 40		1.41		4.0
	40 to 50		...		...

[A] These numbers represent, respectively, the (1S) and (D2S) limits as described in Practice C 670.
[B] These numbers represent, respectively, the (1S %) and (D2S %) limits as described in Practice C 670.
[C] The precision estimates are based on coarse aggregates with nominal maximum size of 19.0 mm (¾ in.).
[D] These values are from precision indices first included in Method C 136 – 77. Other indices were developed in 1982 from more recent AASHTO Materials Reference Laboratory sample data, which did not provide sufficient information to revise the values so noted.

The American Society for Testing and Materials takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, 1916 Race St., Philadelphia, PA 19103.

APPENDIX E

ASTM METHOD FOR THE LOS ANGELES ABRASTION TEST

Designation: C 131 - 89

Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine[1]

This standard is issued under the fixed designation C 131; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers a procedure for testing sizes of coarse aggregate smaller than 1½ in. (37.5 mm) for resistance to degradation using the Los Angeles testing machine.

NOTE 1—A procedure for testing coarse aggregate larger than ¾ in. (19 mm) is covered in Test Method C 535.

2. Referenced Documents

2.1 *ASTM Standards:*

C 136 Method for Sieve Analysis of Fine and Coarse Aggregates[2]

C 535 Test Method for Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine[2]

C 670 Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials[2]

C 702 Practice for Reducing Field Samples of Aggregate to Testing Size[2]

D 75 Practice for Sampling Aggregates[2]

E 11 Specification for Wire-Cloth Sieves for Testing Purposes[3]

3. Summary of Test Method

3.1 The Los Angeles test is a measure of degradation of mineral aggregates of standard gradings resulting from a combination of actions including abrasion or attrition, impact, and grinding in a rotating steel drum containing a specified number of steel spheres, the number depending upon the grading of the test sample. As the drum rotates, a shelf plate picks up the sample and the steel spheres, carrying them around until they are dropped to the opposite side of the drum, creating an impact-crushing effect. The contents then roll within the drum with an abrading and grinding action until the shelf plate impacts and the cycle is repeated. After the prescribed number of revolutions, the contents are removed from the drum and the aggregate portion is sieved to measure the degradation as percent loss.

4. Significance and Use

4.1 The Los Angeles test has been widely used as an indicator of the relative quality or competence of various sources of aggregate having similar mineral compositions. The results do not automatically permit valid comparisons to be made between sources distinctly different in origin, composition, or structure. Specification limits based on this test should be assigned with extreme care in consideration of available aggregate types and their performance history in specific end uses.

5. Apparatus

5.1 *Los Angeles Machine*—The Los Angeles testing machine, conforming in all its essential characteristics to the design shown in Fig. 1, shall be used. The machine shall consist of a hollow steel cylinder, closed at both ends, having an inside diameter of 28 ± 0.2 in. (711 ± 5 mm), and an inside length of 20 ± 0.2 in. (508 ± 5 mm). The cylinder shall be mounted on stub shafts attached to the ends of the cylinder but not entering it, and shall be mounted in such a manner that it may be rotated with the axis in a horizontal position within a tolerance in slope of 1 in 100. An opening in the cylinder shall be provided for the introduction of the test sample. A suitable, dust-tight cover shall be provided for the opening with means for bolting the cover in place. The cover shall be so designed as to maintain the cylindrical contour of the interior surface unless the shelf is so located that the charge will not fall on the cover, or come in contact with it during the test. A removable steel shelf extending the full length of the cylinder and projecting inward 3.5 ± 0.1 in. (89 ± 2 mm) shall be mounted on the interior cylindrical surface of the cylinder, in such a way that a plane centered between the large faces coincides with an axial plane. The shelf shall be of such thickness and so mounted, by bolts or other suitable means, as to be firm and rigid. The position of the shelf shall be such that the distance from the shelf to the opening, measured along the outside circumference of the cylinder in the direction of rotation, shall be not less than 50 in. (1.27 m).

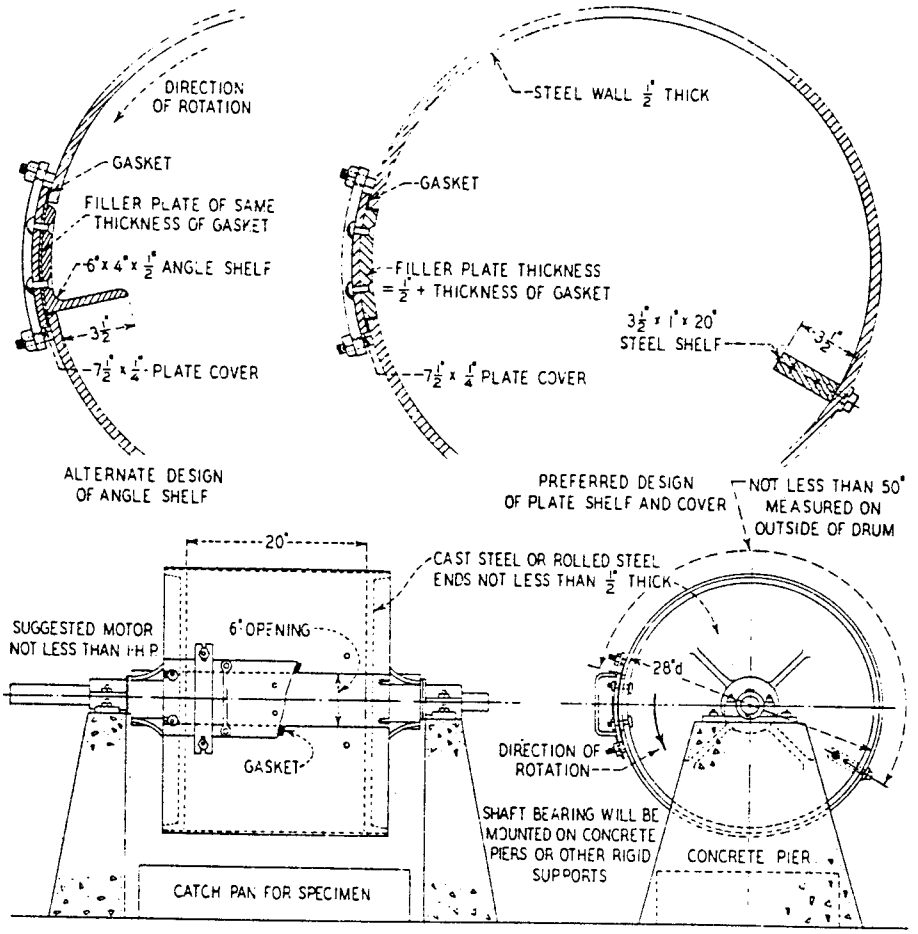
NOTE 2—The use of a shelf of wear-resistant steel, rectangular in cross section and mounted independently of the cover, is preferred. However, a shelf consisting of a section of rolled angle, properly mounted on the inside of the cover plate, may be used provided the direction of rotation is such that the charge will be caught on the outside face of the angle. If the shelf becomes distorted from its original shape to such an extent that the requirements given in X1.2 of the Appendix to this method are not met, the shelf shall either be repaired or replaced before additional tests are made.

[1] This test method is under the jurisdiction of ASTM Committee C-9 on Concrete and Concrete Aggregates and is the direct responsibility of Subcommittee C09.03.05 on Methods of Testing and Specifications for Physical Characteristics of Concrete Aggregates.

Current edition approved June 15, 1989. Published June 1989. Originally published as C 131 - 37 T. Last previous edition C 131 - 81(1987).

[2] *Annual Book of ASTM Standards*, Vols 04.02 and 04.03.

[3] *Annual Book of ASTM Standards*, Vol 14.02.



Metric Equivalents

in.	1/4	1/2	1	3 1/2	4	6	7 1/2	20	28	50
mm	6.4	12.7	25.4	89	102	152	190	508	711	1270

FIG. 1 Los Angeles Testing Machine

5.1.1 The machine shall be so driven and so counterbalanced as to maintain a substantially uniform peripheral speed (Note 3). If an angle is used as the shelf, the direction of rotation shall be such that the charge is caught on the outside surface of the angle.

NOTE 3—Back-lash or slip in the driving mechanism is very likely to furnish test results which are not duplicated by other Los Angeles machines producing constant peripheral speed.

5.2 *Sieves*, conforming to Specification E 11.

5.3 *Balance*—A balance or scale accurate within 0.1 % of test load over the range required for this test.

5.4 *Charge*—The charge shall consist of steel spheres averaging approximately 1 27/32 in. (46.8 mm) in diameter and each weighing between 390 and 445 g.

5.4.1 The charge, depending upon the grading of the test sample as described in Section 7, shall be as follows:

Grading	Number of Spheres	Weight of Charge, g
A	12	5000 ± 25
B	11	4584 ± 25
C	8	3330 ± 20
D	6	2500 ± 15

NOTE 4—Steel ball bearings 1 13/16 in. (46.0 mm) and 1 7/8 in. (47.6 mm) in diameter, weighing approximately 400 and 440 g each, respectively, are readily available. Steel spheres 1 27/32 in. (46.8 mm) in diameter weighing approximately 420 g may also be obtainable. The charge may consist of a mixture of these sizes conforming to the weight tolerances of 5.4 and 5.4.1.

6. Sampling

6.1 The field sample shall be obtained in accordance with Practice D 75 and reduced to test portion size in accordance with Methods C 702.

7. Test Sample

7.1 The test sample shall be washed and oven-dried at 221 to 230°F (105 to 110°C) to substantially constant weight (Note 5), separated into individual size fractions, and recombined to the grading of Table 1 most nearly corresponding to the range of sizes in the aggregate as furnished for the work. The weight of the sample prior to test shall be recorded to the nearest 1 g.

8. Procedure

8.1 Place the test sample and the charge in the Los Angeles testing machine and rotate the machine at a speed of 30 to 33 rpm for 500 revolutions. After the prescribed number of revolutions, discharge the material from the

TABLE 1 Gradings of Test Samples

Sieve Size (Square Openings)		Weight of Indicated Sizes, g			
		Grading			
Passing	Retained on	A	B	C	D
37.5 mm (1½ in.)	25.0 mm (1 in.)	1 250 ± 25	...	...	...
25.0 mm (1 in.)	19.0 mm (¾ in.)	1 250 ± 25	...	...	...
19.0 mm (¾ in.)	12.5 mm (½ in.)	1 250 ± 10	2 500 ± 10	...	...
12.5 mm (½ in.)	9.5 mm (⅜ in.)	1 250 ± 10	2 500 ± 10	...	...
9.5 mm (⅜ in.)	6.3 mm (¼ in.)	...	...	2 500 ± 10	...
6.3 mm (¼ in.)	4.75-mm (No. 4)	...	...	2 500 ± 10	...
4.75-mm (No. 4)	2.36-mm (No. 8)	...	...	...	5 000 ± 10
Total		5 000 ± 10	5 000 ± 10	5 000 ± 10	5 000 ± 10

machine and make a preliminary separation of the sample on a sieve coarser than the 1.70-mm (No. 12). Sieve the finer portion on a 1.70-mm sieve in a manner conforming to Method C 136. Wash the material coarser than the 1.70-mm sieve (Note 5), oven-dry at 221 to 230°F (105 to 110°C) to substantially constant weight, and weigh to the nearest 1 g (Note 6).

NOTE 5—If the aggregate is essentially free of adherent coatings and dust, the requirement for washing before and after test may be waived. Elimination of washing after test will seldom reduce the measured loss by more than about 0.2 % of the original sample weight.

NOTE 6—Valuable information concerning the uniformity of the sample under test may be obtained by determining the loss after 100 revolutions. This loss should be determined without washing the material coarser than the 1.70-mm sieve. The ratio of the loss after 100 revolutions to the loss after 500 revolutions should not greatly exceed 0.20 for material of uniform hardness. When this determination is made, take care to avoid losing any part of the sample; return the entire sample, including the dust of fracture, to the testing machine for the final 400 revolutions required to complete the test.

9. Calculation

9.1 Express the loss (difference between the original weight and the final weight of the test sample) as a percentage of the original weight of the test sample. Report this value as the percent loss.

NOTE 7—The percent loss determined by this method has no known consistent relationship to the percent loss for the same material when tested by Test Method C 535.

10. Precision

10.1 For nominal 19.0-mm (¾-in.) maximum size coarse aggregate with percent losses in the range of 10 to 45 %, the multilaboratory coefficient of variation has been found to be 4.5 %.[4] Therefore, results of two properly conducted tests from two different laboratories on samples of the same coarse aggregates should not differ from each other by more than 12.7 %[4] of their average. The single-operator coefficient of variation has been found to be 2.0 %.[4] Therefore, results of two properly conducted tests by the same operator on the same coarse aggregate should not differ from each other by more than 5.7 % of their average.[4]

10.2 *Bias*—Since there is no accepted reference material suitable for determining the bias for this procedure, no statement on bias is being made.

[4] These numbers represent, respectively, the (1S%) and (D2S%) limits as described in Practice C 670.

APPENDIX

(Nonmandatory Information)

X1. MAINTENANCE OF SHELF

X1.1 The shelf of the Los Angeles machine is subject to severe surface wear and impact. With use, the working surface of the shelf is peened by the balls and tends to develop a ridge of metal parallel to and about 1¼ in. (32 mm) from the junction of the shelf and the inner surface of the cylinder. If the shelf is made from a section of rolled angle, not only may this ridge develop but the shelf itself may be bent longitudinally or transversely from its proper position.

X1.2 The shelf should be inspected periodically to determine that it is not bent either lengthwise or from its normal radial position with respect to the cylinder. If either condition is found, the shelf should be repaired or replaced before further tests are made. The influence on the test result of the ridge developed by peening of the working face of the shelf is not known. However, for uniform test conditions, it is recommended that the ridge be ground off if its height exceeds 0.1 in. (2 mm).

The American Society for Testing and Materials takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, 1916 Race St., Philadelphia, PA 19103.

APPENDIX F

STATE DERIVED AGGREGATE DURABILITY TESTS

The following pages contain state-derived durability tests for construction aggregtes based on AASHTO Method T-210 and ASTM Method D 3744. Test methods derived by Washington, Main, and Alaska are provided.

WASHINGTON DEGRADATION TEST PROCEDURE

Following is the procedure for performing the Washington Degradation Test, Revised 1962, as modified by the Maine Department of Transportation.

Equipment

Balance, minimum 800 gm capacity, sensitive to 0.1 gm

Sieve Shaker - Soiltest #CL300

Plastic Canister, 6" high 7½" diameter, Tupperware, with cover

Sand Equivalent Cylinder

Sand Equivalent Stock Solution

Sieves - 1/2", 1/4", #10, #200

Graduate 500 ml, 10 ml

Interval Timer

Funnel, 9"

Squeeze Bottle, 500 ml

Test Method

The material to be tested shall pass the 1/2" sieve, be washed over a #10 sieve and dried to constant weight. Make up sample graded as follows:

1/2" - 1/4"	500 grams
1/4" - U.S. #10	500 grams

Part I

Place sample in a 7 1/2" diameter x 6" high plastic canister (tupperware), add 200 cc water, cover tightly, and place in a Tyler Portable Sieve Shaker (Soiltest #CL-300, 305, suitably motored to provide oscillation described below). *Run shaker for twenty minutes at 215 oscillations per minute with a 2 1/8" throw on the cam. At the conclusion of shaking time, empty the canister into nested #10 and #200 sieves, placed in a funnel over a 500 ml graduate to catch all water. Wash out the canister and continue to wash the aggregate with fresh water from squeeze bottle until the graduate is filled to the 500 ml mark.

Caution: The aggregate may drain 50 - 100 ml of water after washing has been stopped. Save all aggregate!

Pour 7 ml of sand equivalent stock solution (see AASHTO T-176-73) into a sand equivalent cylinder. Bring all solids in the wash water into suspension by capping the graduate with the palm of the hand, then turning the cylinder upside down and right side up as rapidly as possible about ten times. Immediately pour the liquid into the sand equivalent cylinder to the 15" mark.

Cap cylinder with stopper, hand or other suitable means, and mix the contents of the sand equivalent cylinder by alternately turning the cylinder upside down and right side up, allowing the bubble to transverse completely from end to end. Repeat this cycle twenty times as rapidly as possible.

*It is essential that the portable field sieve shaker be checked against the Central Lab shaker by running degradation values on check samples.

At the conclusion of the mixing time, pleace the cylinder on the table, remove the stopper and start the timer. After twenty minutes read and record the height of the sediment column to the nearest 0.1 inch.

Part II

Place the aggregate retained on the #10 and #200 sieves in oven until dry, then sieve and record the weights retained on U.S. #10 and #200 sieves. Loss through each sieve is determined by subtraction from original weight, and recorded to nearest gram.

Calculations:

Calculate the degradation factor by the following formula:

$$D = \left[0.3 \left(1.00 - \frac{L_{200}}{L_{10}} \right) + 0.7 \left(\frac{6 - 0.4H}{6 + 0.6H} \right) \right] \times 100$$

Where D = degradation factor

L_{200} = grams lost through #200 sieve

L_{10} = grams lost through #10 sieve

H = height of sediment in tube

This formula gives a weight of 30 percent to the ratio of the loss through the #200 and #10 sieves, and 70 percent to the quality of the fines as determined by the cleanness portion of the test. Values will range from 0 to 100, with high values being best materials.

MAINE TEST METHOD FOR DETERMINING AGGREGATE DEGRADATION

1. SCOPE:

   A. This test method details a procedure for determining the susceptibility of an aggregate to degrade and the quality of the fines produced by self-abrasion in the presence of water.

2. APPARATUS:

   A. Balance - 800 gram capacity, sensitive to 0.1 gm.

   B. Sieve shaker - Tyler portable model, ± 1 3/4" throw on cam at ±300 oscillations per minute.

   C. Plastic Canister - 7 1/2" in diameter x 6" high ("Tupperware") with cover.

   D. Sand Equivalent Cylinder.

   E. Sand Equivalent Stock Solution (AASHTO T-176-73).

   F. Sieves 1/2", 1/4" - U.S. No. 10 and U.S. No. 200.

   G. Graduates - 500 ml tall form, 10 ml.

   H. Interval Timer.

   I. Funnel, 9".

   J. Squeeze Bottle, 500 ml.

3. PROCEDURE:

   A. Sieve the material to be tested through the 1/2" sieve, wash over a No. 10 sieve and dry to constant weight.

   B. 1000 g sample of the aggregate graded as follows:

      1/2 in. - 1/4 in. . . . . 500 g
      1/4 in. - U.S. No. 10 . . . . . 500 g

C. Place sample in the plastic canister, add 200 cc of water, cover tightly and place in sieve shaker.

D. Agitate the material for 20 minutes.

E. Empty the canister into nested No. 10 and No. 200 sieves placed in a funnel over a 500 ml graduate to catch all the water.

F. Wash out the canister and continue to wash the aggregate with fresh water from the squeeze bottle until the graduate is filled to the 500 ml mark. (The aggregate may drain 50-100 ml of water after washing has been stopped).

G. Pour 7 ml of sand equivalent stock solution into a sand equivalent cylinder.

H. Bring all solids in the graduate into suspension by capping the graduate with the palm of the hand and turning it upside down and back as rapidly as possible about 10 times.

I. Immediately decant into the sand equivalent cylinder to the 15" mark and insert stopper in the cylinder, or cover with hand.

J. Mix the contents of the cylinder by alternately turning the cylinder upside down and right side up, allowing the bubble to transverse from end to end. Repeat this cycle 20 times as rapidly as possible.

K. Place the cylinder on the table, remove stopper and start timer. After 20 minutes read and record the height of the sediment column to the nearest 0.1".

4. CALCULATIONS:

A. Calculate the degradation factor by the following formula:

$$DF = \frac{(15-H)}{(15+1.75H)} \times 100$$ or use Table 1

where:

DF = Degradation Factor
H = Height of Sediment in Tube.

B. Values may range from 0 to 100, with high values being best materials.

5. REPORTS:

A. All test results shall be reported on Form TL-88(1/81).

STANDARD METHOD OF TEST FOR DEGRADATION OF AGGREGATES

A. SCOPE:

This method of test covers a procedure for determining the susceptibility of an aggregate to degradation during agitation in water.

B. APPARATUS:

1. Balance — The balance shall be sensitive to 1.0 gram with a minimum capacity of 500 grams.
2. Sieves — The sieves shall conform to AASHTO M-92. Sizes 1/2-inch, 1/4-inch, No. 10 and No. 200 are required.
3. Sieve Shaker — The sieve shaker shall be a portable model suitably motorized to provide 300 + 10 oscillations per minute with a 1 3/4-inch throw on the cam. It shall be calibrated against the sieve shaker at the Regional Materials Laboratory before use.
4. Plastic Canister — The plastic canister shall be "Tupper Ware", 7 1/2" in diameter and 6" in height, having a flat bottom.
5. Miscellaneous — Standard Sand Equivalent Cylinder, Sand Equivalent Solution*, funnel with 9" mouth, ring and ring stand, polyethylene wash bottle, 500 ml. graduate, rubber or cork stoppers, 10 ml. capacity graduated cylinder, drying oven.

C. SAMPLE PREPARATION:

1. Crush a representative sample of the plus No. 4 material to be tested to pass the 1/2 inch sieve. There will be some material that will pass through the crusher uncrushed.
2. Wash over a No. 10 sieve and dry to a constant weight.
3. Separate the sample into two sizes, 1/2-inch to 1/4-inch and 1/4-inch to No. 10, and weigh out 500 gms. of each size to the nearest 1.0 gm.

D. PROCEDURE:

1. Place both sample portions in the plastic canister, add 200 ml. of water, and cover tightly. Place the canister in the shaker and run for 20 minutes.
2. Stack a No. 10 and No. 200 sieve inside the large funnel. Support the funnel with a ring and ring stand over the 500 ml. graduate.

* Sand Equivalent Stock Solution to be supplied by the Central Material Laboratory

3. Wash the contents of the canister over the No. 10 and No. 200 sieves and continue washing until wash water has reached the 500 ml. mark on the graduate. Washing may be facilitated by agitating the nest of sieves. In instances where highly degradable materials are encountered and the sample cannot be washed clean with 500 ml. of water, continue washing using water sparingly, until sample is washed clean. In no instance, however, shall the total volume of water be greater than 1000 ml. Allow the wash water to settle until clear, then siphon or pipette the extra water to 500 ml. being careful not to disturb the settled material.
4. Pour 7 ml. of stock sand equivalent solution into the sand equivalent cylinder. Bring all solids in the wash water into suspension by clapping the graduate with the palm or a rubber stopper, then turn the graduate upside down and right side up 10 times. Immediately fill the sand equivalent cylinder to the 15" mark and insert rubber stopper in cylinder.
5. Mix the contents of the sand equivalent cylinder by alternately inverting and righting the cylinder allowing the bubble to traverse from one end to the other and back again. This is one cycle. Repeat this cycle 20 times as rapidly as possible.
6. Remove the stopper and place the cylinder on the table. Allow the cylinder to set undisturbed for 20 minutes, then read and record the height of the sediment to the nearest 0.1 inch.

E. CALCULATIONS:

1. Calculate the degradation factor by the following formula:

$$D = \frac{15 - H}{15 + 1.75\,H}(100)$$

Where: D = Degradation factor
H = Height of sediment in cylinder.

or use Table I.

2. Values may range from 0 to 100, with high values being more suitable material.

F. REPORTING RESULTS:

Use appropriate lab worksheet, and report date on form 25-229.

TABLE I
DEGRADATION VALUE "D"

$$D = \frac{15 - H}{15 + 1.75H} (100)$$

H	D	H	D	H	D	H	D	H	D
0.1	98	3.1	58	6.1	35	9.1	19	12.1	8
0.2	96	3.2	57	6.2	34	9.2	19	12.2	8
0.3	95	3.3	56	6.3	33	9.3	18	12.3	7
0.4	93	3.4	55	6.4	33	9.4	18	12.4	7
0.5	91	3.5	54	6.5	32	9.5	17	12.5	7
0.6	90	3.6	54	6.6	32	9.6	17	12.6	6
0.7	88	3.7	53	6.7	31	9.7	17	12.7	6
0.8	87	3.8	52	6.8	30	9.8	16	12.8	6
0.9	85	3.9	51	6.9	30	9.9	16	12.9	6
1.0	84	4.0	50	7.0	29	10.0	15	13.1	5
1.1	82	4.1	49	7.1	29	10.1	15	13.1	5
1.2	81	4.2	48	7.2	28	10.2	15	13.2	5
1.3	79	4.3	48	7.3	28	10.3	14	13.3	4
1.4	78	4.4	47	7.4	27	10.4	14	13.4	4
1.5	77	4.5	46	7.5	27	10.5	13	13.5	4
1.6	75	4.6	45	7.6	26	10.6	13	13.6	4
1.7	74	4.7	44	7.7	26	1.7	13	13.7	3
1.8	73	4.8	44	7.8	25	10.8	12	13.8	3
1.9	71	4.9	43	7.9	25	10.9	12	13.9	3
2.0	70	5.0	42	8.0	24	11.0	12	14.0	3
2.1	69	5.1	41	8.1	24	11.1	11	14.1	2
2.2	68	5.2	41	8.2	23	11.2	11	14.2	2
2.3	67	5.3	40	8.3	23	11.3	11	14.3	2
2.4	66	6.4	39	8.4	22	11.4	10	14.4	1
2.5	65	5.5	39	8.5	22	11.5	10	14.5	1
2.6	63	4.5	38	8.6	21	11.6	10	14.6	1
2.7	62	5.7	37	8.7	21	11.7	9	14.7	1
2.8	61	5.8	37	8.8	20	11.8	9	14.8	0
2.9	60	5.9	36	8.9	20	11.9	9	14.9	0
3.0	59	6.0	35	9.0	20	12.0	8	15.0	0

F. REPORTING RESULTS:

Report data using form 25-229

(7-79)

APPENDIX G

ASTM METHOD E 384-89 FOR VICKERS HARDNESS

Standard Test Method for Microhardness of Materials[1]

This standard is issued under the fixed designation E 384; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers determination of the microhardness of materials, the verification of microhardness testing machines, and the calibration of standardized test blocks. Appendix X1 provides guidance in establishing correlation of microhardness tests when two or more laboratories are involves.

1.2 *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

E 3 Methods of Preparation of Metallographic Specimens[2]

E 122 Practice for Choice of Sample Size to Estimate the Average Quality of a Lot or Process[3]

E 175 Definitions of Terms Relating to Microscopy[4]

E 691 Practice for Conducting an Interlaboratory Test Program to Determine the Precision of Test Methods[3]

A. TEST PROCEDURE

3. Scope

3.1 This procedure covers tests made with the Knoop and Vickers indenters under test loads in the range from 1 to 1000 gf.

NOTE 1—While Committee E-4 is primarily concerned with metals, the test procedures described are applicable to all types of materials, and not merely to metals.

4. Terminology

4.1 *Definitions:*

4.1.1 *microhardness test*—a microindentation hardness test using a calibrated machine to force a diamond indenter of specific geometry, under a test load of 1 to 1000 gf, into the surface of the test material and to measure the diagonal or diagonals optically.

4.1.2 *Knoop hardness number (HK)*—the number obtained by dividing the applied load in kilograms-force by the projected area of the indentation in square millimetres, computed from the measurement of the long diagonal of the indentation. It is assumed that the indentation is an imprint of the undeformed indenter (see Fig. 1).

Discussion—The Knoop hardness number is computed from the following equation:

$$HK = P/A_p = P/d^2c = P/0.07028d^2 = 14.229P/d^2 \quad (1)$$

where:

P = load, kgf,

A_p = projected area of indentation, mm^2,

d = length of long diagonal, mm, and

c = indenter constant relating projected area of the indentation to the square of the length of the long diagonal.

Discussion—Since the units normally used are grams-force and micrometres rather than kilograms-force and millimetres, the equation for the Knoop hardness number can be expressed conveniently as:

$$HK = 14229P_1/d_1^2 \quad (2)$$

where:

P_1 = load, gf, and

d_1 = length of long diagonal μm.

Discussion—The Knoop hardness numbers are given in Table 1 for a test load of 1 gf. For obtaining hardness numbers when other test loads are used, the Knoop hardness number, obtained from Table 1, is multiplied by the test load in grams-force.

4.1.3 *Vickers hardness number (HV)*—the number obtained by dividing the applied load in kilograms-force by the surface area of the indentation in square millimetres computed from the mean of the measured diagonals of the indentation. It is assumed that the indentation is an imprint of the undeformed indenter (Fig. 2).

Discussion—The Vickers hardness number is computed from the following equation:

$$HV = P/A_s = 2P\sin(\alpha/2)/d^2 = 1.8544P/d^2 \quad (3)$$

where:

P = load, kgf,

A_s = surface area of indentation, mm^2,

d = mean diagonal of indentation, mm, and

α = face angle of indenter = 136°.

Discussion—Since the units normally used are grams-force and micrometres rather than kilograms-force and millimetres, the equation for the Vickers hardness number can be expressed conveniently as:

$$HV = 1854.4P_1/d_1^2 \quad (4)$$

where:

P_1 = load, gf, and

d_1 = mean diagonal of indentation, μm.

Discussion—The Vickers hardness numbers are given in Table 2 for a test load of 1 gf. For obtaining hardness

[1] This test method is under the jurisdiction of ASTM Committee E-4 on Metallography and is the direct responsibility of Subcommittee E04.05 on Microhardness.

Current edition approved Oct. 17, 1989. Published April 1990. Originally published as E 384 – 69. Last previous edition E 384 – 84.

[2] *Annual Book of ASTM Standards*, Vol 03.01.

[3] *Annual Book of ASTM Standards*, Vol 14.02.

[4] *Annual Book of ASTM Standards*, Vol 14.01.

numbers when other test loads are used, the Vickers hardness number obtained from Table 2 is multiplied by the test load in grams-force.

4.1.4 *verification*—checking or testing to assure conformance with the specification.

4.1.5 *calibration*—determination of the values of the significant parameters by comparison with values indicated by a reference instrument or by a set of reference standards.

5. Apparatus

5.1 *Testing Machine*—Equipment for microhardness testing usually consists of a testing machine that supports the specimen and permits the indenter and specimen to be brought into contact gradually and smoothly under a predetermined load. The design of the machine should be such that no rocking or lateral movement of the indenter or specimen is permitted while the load is being applied or removed. A measuring microscope is usually mounted on the machine in such a manner that the indentation may be readily located in the field of view.

5.1.1 *Load Application:*

5.1.1.1 The plane of the surface of the specimen shall be perpendicular to the axis of the direction of the load application.

5.1.1.2 The indenter shall contact the specimen at a velocity in the range from 15 to 70 µm/s.

5.1.1.3 The time of application of the full test load shall be 10 to 15 s unless otherwise specified.

5.1.2 *Vibration Control:*

5.1.2.1 The microhardness testing machine shall be located in an area as free from vibrations as possible in order to avoid erroneous results. When test loads of 100 gf to less than 500 gf are employed, the machine shall be isolated in such a manner that vibrational accelerations of 0.005 *g* (2 in./s^2) or larger are not applied to the machine frame. For test loads less than 100 gf the maximum allowable vibrational accelerations inadvertently reaching the machine should be held proportionately lower than the 0.005 *g* limit.

5.1.2.2 Operators of microhardness testing machines in which the indenter contacts and leaves the work surface by manual control should take care to perform all operations slowly and smoothly.

5.1.2.3 At no time during the period of indenter contact should the operator inadvertently contact the machine frame so as to subject it to vibrational accelerations in excess of 0.005 *g*.

5.2 *Indenters:*

5.2.1 *Knoop Indenter*—A highly polished, pointed, rhombic-based, pyramidal diamond with included longitudinal edge angles of 172° 30 min (±5 min) and 130° 0 min. The indenter constant, *c*, shall differ from 0.07028 by not more than 1 %.

5.2.1.1 The four faces of the indenter shall be equally inclined to the axis of the indenter (within ±30 min) and shall meet at a sharp point. The line of junction between opposite faces (offset) shall be not more than 1.0 µm in length for indentations greater than 15 µm in length, as shown in Fig. 3. For shorter indentations the offset should be proportionately less.

5.2.1.2 The diamond shall be examined periodically; and if it is loose in the mounting material, chipped or cracked, it should be replaced.

5.2.2 *Vickers Indenter*—A highly polished, pointed, square-based pyramidal diamond with face angles of 136° 0 min (±30 min).

5.2.2.1 The four faces of the indenter shall be equally inclined to the axis of the indenter (within ±30 min) and shall meet at a sharp point. The line of junction between opposite faces (offset) shall be not more than 0.5 µm in length, as shown in Fig. 4.

5.2.2.2 The diamond should be examined periodically; and if it is loose in the mounting material, chipped or cracked, it should be replaced.

5.3 *Measuring Equipment*—The measuring microscope at highest magnification shall be graduated in 0.5-µm or smaller divisions.

5.3.1 *Microscope Objectives and Ocular*—The optical portion of the measuring equipment shall have Kohler or Abbé-Nelson illumination (Annex A1).

5.3.1.1 For maximum resolution, provisions shall be made for the adjustment of the illumination intensity and concentration, the aperture diaphragm, and the field diaphragm. The ocular shall be of the filar micrometer type as defined in Definitions E 175. The objective shall be of a type for use without a cover glass.

5.3.1.2 Magnification for range of indentation length is indicated as follows:

	Magnification	
Indentation Length, µm	max	min
Less than 76	...	400
76 to 125	800	300
Greater than 125	600	200

5.3.1.3 *Illumination*—Proper illumination is necessary in order to obtain optimum resolution from a microscope. There are two systems which give proper illumination. Abbé-Nelson or "critical" is the system in which the image of the illuminating source is focused in the plane of the specimen. Kohler illumination is the system in which the illuminating source is imaged at the near focal plane of the objective lens. (Abbé-Nelson and Kohler illumination adjustment techniques are given in Annex A1.)

6. Specimen Mounting

6.1 Mounting is recommended for convenience in surface preparation and testing. The specimen should be adequately supported in the mounting medium.

6.2 Where edge retention is not essential, the specimen may or may not be mounted. If mounted, a softer mounting material may be used. However, the material must have sufficient rigidity so that no movement of the specimen can occur during the application of load.

7. Test Specimens

7.1 *Surface Preparation:*

7.1.1 *Degree of Finish*—The degree of surface finish required can vary with the several loads and magnifications used in microhardness testing. However, in all tests the perimeter of the indentation must be clearly defined in the field of the microscope.

7.1.2 *Grinding and Polishing*—When grinding or polishing, or both is necessary in specimen preparation, care

should be taken to minimize heating and distorting the specimen surface. Polishing should be performed according to the procedures outlined in Methods E 3.

8. Procedure

8.1 Support the specimen so that the test surface is normal to the axis of the indenter and the ends of the diagonals are clearly defined (see 8.4).

8.2 Space the indentations so that the distance between any two indentations is greater than twice the extent of any stress deformation (cold working, "butterfly" fractures, etc) that may occur as a result of the indentation process so that there shall be no overlap of the deformation between two indentations.

8.3 Adjust optical equipment (Section 5).

8.4 *Measure Indentation*—Having completed the adjustment of the optical system, when applicable, and having selected the correct objective, bring the ends of the diagonal(s) into sharp focus. Examine the indentation for symmetry prior to measurement.

8.4.1 *Knoop Indentation*—If one leg of the long diagonal is more than 20 % longer than the other, or if the ends of the diagonal are not both in the field of focus, the surface of the specimen may not be normal to the axis of the indenter. Align the specimen surface properly, and make another indentation.

8.4.2 *Vickers Indentation*—If one leg of a diagonal is noticeably longer than the other leg of the same diagonal, resulting in a deformed indentation, misalignment is probably present and should be corrected before proceeding with any measurements.

8.4.3 To determine the source of misalignment, rotate the specimen 90 or 180° and make a second indentation. If the deformed shape of the second indentation has also rotated, the surface is at fault and shall be properly aligned. If the deformed shape has not rotated, examine the indenter seat for dirt or nicks which may cause misalignment of the indenter.

NOTE 2—It should be pointed out that there are a few materials that may show deformed indentations even though the specimen and indenter are properly aligned. Therefore, in the situation where realignment has not corrected the problem, use another material known to give symmetrical indentations to check the alignment of the setup.

8.4.4 Make any micrometer screw motion required for the measurement of the indentation in the same direction to eliminate errors due to the backlash of the screw thread.

8.4.5 Bring the edge of the ocular or graduation line just into contact with the end of the diagonal. This is particularly important since the precision of the measurement of the diagonal is dependent upon the initial positioning of the graduation line. To eliminate the influence of the thickness of the line, always use the same edge of the graduation line.

8.4.6 *Knoop Indentation*—Read the long diagonal of the indentation to within 0.25 µm or 0.4 %, whichever is larger.

8.4.7 *Vickers Indentation*—Read the two diagonals of the indentation to within 0.25 µm or 0.4 %, whichever is larger; and determine the average of the diagonal lengths.

8.5 *Determination of Hardness Numbers:*

8.5.1 Compute the Knoop hardness number from the equation given in 4.2.1.1 or from the information given in Table 1. To obtain the hardness number from the table, read the HK (1 gf) corresponding to the measured diagonal length in micrometres and multiply by the test load in grams-force.

8.5.2 Compute the Vickers hardness number from the equation given in 4.3.1.1 or from the information given in Table 2. To obtain the hardness number from the table, read the HV (1 gf) corresponding to the average of the measured diagonal lengths in micrometres and multiply by the test load in grams-force.

9. Precision and Bias[5]

9.1 The precision and bias of microhardness measurements depend on strict adherence to the stated test procedure and are influenced by instrumental and material factors and indentation measurement errors.

9.2 The consistency of agreement for repeated tests on the same material is dependent on the homogeneity of the material, reproducibility of the hardness tester, and consistent, careful measurement of the indents by a competent operator.

9.3 Instrumental factors that can affect test results include: accuracy of loading, inertia effects, speed of loading, vibrations, the angle of indentation, lateral movement of the indenter or sample, indentation and indenter shape deviations.

9.3.1 Vibrations during indenting will produce larger indents with the influence of vibrations becoming larger as the load decreases (**1, 2**).[6]

9.3.2 The angle between the indenter and specimen surface should be within 2° perpendicular. Greater amounts of tilting produces nonuniform indentations and invalid test results.

9.4 Material factors that can affect test results include: sample homogeneity, orientation/texture effects, improper specimen preparation, low specimen surface reflectivity, and transparency of the specimen.

9.4.1 Residual deformation from mechanical polishing must be removed, particularly for low-load testing.

9.4.2 Distortion of the indent shape due to either crystallographic or microstructural texture influences diagonal lengths and the validity of the calculated hardness.

9.4.3 Metal deformation during indentation can produce ridging around the indent periphery that will affect diagonal measurement accuracy.

9.4.4 Testing of etched surfaces, depending on the extent of etching, can produce results that are different from those obtained on unetched surfaces (**1**).

9.5 Measurement errors that can affect test results include: inaccurate calibration of the measuring device, inadequate resolving power of the objective, insufficient magnification, operator bias in sizing the indents, poor image quality, and nonuniform illumination.

9.5.1 The accuracy of microindentation hardness testing is strongly influenced by the accuracy to which the indents can be measured.

9.5.2 The error in measuring the diagonals increases as

[5] Supporting data have been filed at ASTM Headquarters and may be obtained by requesting RR: E-04.

[6] The boldface numbers in parentheses refer to the list of references at the end of this standard.

the numerical aperture of the measuring objective decreases (3, 4).

9.5.3 Bias is introduced if the operator consistently undersizes or oversizes the indents.

9.6 Some of the factors that affect test results produce systematic errors that influence all test results while others primarily influence low-load test results. Some of these problems occur continually, others may occur in an undefined, sporadic manner. Low load hardness tests are influenced by these factors to a greater extent than high load tests.

9.6.1 Due to the relationship between the diagonal length and the calculated Knoop or Vickers hardness (see Eq 2 and 4), measurement errors of the same magnitude cause proportionally greater hardness variability as the indent size decreases.

9.7 An interlaboratory test program was conducted in accordance with Practice E 691 to develop information regarding the precision, repeatability, and reproducibility of the measurement of Knoop and Vickers indentations made using loads of 25, 50, 100, 200, 500, and 1000 gf on three ferrous and four nonferrous samples.[5] Twelve laboratories measured the indents, five of each type at each load on each sample. Additional details of this study are given in Appendix X2.

9.7.1 Tests of the three ferrous samples revealed that nine laboratories produced similar measurements while two laboratories consistently undersized the indents and one laboratory consistently oversized the indents. These latter results were most pronounced as the load decreased and sample hardness increased (that is, as the diagonal size decreased) and were observed for both Vickers and Knoop indents. Results for the lower hardness nonferrous indents produced better agreement. However, none of the laboratories that obtained higher or lower results on the ferrous samples measured the nonferrous indents.

9.7.2 *Repeatability Interval*—The difference due to test error between two test results in the same laboratory on the same material increases with increasing specimen hardness and with decreasing test load (see X2.5.4).

9.7.3 *Reproducibility Interval*—The difference in test results on the same material tested in different laboratories increased with increasing specimen hardness and with decreasing test load (see X2.5.5).

9.7.4 The within-laboratory and between-laboratory precision values improved as specimen hardness decreased and test load increased. The repeatability interval and reproducibility interval were generally larger than the precision estimate, particularly at low test loads and high sample hardnesses.

10. Conversion to Other Hardness Scales or Tensile-Strength Values

10.1 There is no generally accepted method for accurate conversion of Knoop or Vickers hardness numbers to other hardness scales or tensile-strength values. Such conversions are limited in scope and should be used with caution, except for special cases where a reliable basis for the conversion has been obtained by comparison tests.

11. Report

11.1 The report shall include the following:

11.1.1 Hardness number,

11.1.2 Test load,

11.1.3 Time of full load application if other than 10 to 15 s,

11.1.4 Magnification, and

11.1.5 Any unusual conditions encountered during the test.

11.2 The hardness number shall be reported as HK for Knoop hardness or HV for Vickers hardness. The load shall be reported in grams-force by subscript notation following the HK or HV, for example, 400 HK_{100}.

B. VERIFICATION OR MICROHARDNESS TESTING MACHINES

12. Scope

12.1 Part B covers two procedures for the verification of microhardness testing machines and a procedure that is recommended for use to confirm that the machine has not become maladjusted in the intervals between periodic routine checks. The two methods of verification are:

12.1.1 Separate verification of load, indenter, and measuring microscope. This procedure is mandatory only for new and rebuilt machines and is the responsibility of the manufacturer.

12.1.2 Verification by standardized test block method. This procedure shall be used for verifying machines in service.

13. General Requirements

13.1 Before a microhardness testing machine is verified the machine shall be examined to ensure that:

13.1.1 The machine is properly set up, and

13.1.2 The load can be applied and removed without shock or vibration in such a manner that the readings are not influenced.

14. Verification

14.1 *Separate Verification of Load, Indenter, and Measuring Microscope*—This procedure is mandatory for new and rebuilt machines and is the responsibility of the manufacturer.

14.1.1 *Load*—When the load is applied by a lever system with dead weights, the combined accuracy of lever distances and dead weights shall be ±0.2 % at the indenter. When the load is applied by direct loading with dead weights, the weights shall be accurate to ±0.2 %.

14.1.2 *Indenter*—The form of the diamond indenter shall be verified by direct measurement of its shape or by measurement of its projection on a screen.

14.1.2.1 For laboratory or routine tests the indenter shall meet the requirements of 5.2.

14.1.2.2 Knoop diamond indenters used for calibrating standardized hardness test blocks shall have included longitudinal edge angles of 172°, 30 min (±5 min) and 130°, 0 min (±5 min), and the offset shall not be more than 0.5 μm.

14.1.2.3 Vickers diamond indenters used for calibrating standardized hardness test blocks shall have face angles of 136°, 0 min (±15 min), and the offset shall not be more than 0.25 μm.

14.1.3 *Measuring Microscope*—The measuring microscope or other device for measuring the diagonals of the

indentation shall be calibrated against an accurately ruled line scale (stage micrometer). The errors of the line scale shall not exceed 0.05 μm or 0.05 % of any interval, whichever is greater. The measuring microscope shall be calibrated in the range of its use, and a calibration factor shall be chosen such that the error shall not exceed ±0.5 %.

14.2 *Verification by Standardized Test Block Method:*

14.2.1 A microhardness testing machine may be checked by making a series of indentations on standardized hardness test blocks.

14.2.2 Make a minimum of five indentations on a test block using a test load applied for 10 to 15 s.

14.2.3 Consider the microhardness testing machines verified if the mean diagonal for five indentations meets the requirements of Section 15.

14.2.4 Verification with standardized test blocks is not recommended if the combination of hardness and test load results in indentations having diagonals less than 20 μm because, under such conditions, the error in the standard micrometer microscope can represent a significant percentage of the diagonal length. Under these circumstances this method of verification does not offer a reliable means of verifying the equipment.

15. Repeatability and Error

15.1 *Repeatability:*

15.1.1 For each standardized block, let $d_1, d_2, \ldots, d_5$ be the diagonal lengths of the indentations, arranged in increasing order of magnitude.

15.1.2 The repeatability of the machine is expressed by the quantity $d_5 - d_1$.

15.1.3 The repeatability is considered satisfactory if it meets the condition given in Table 3.

15.2 *Error:*

15.2.1 The error of the machine is expressed by the quantity $\bar{d}_s - d$, and $\bar{d} = (d_1 + d_2 \ldots d_5)/5$, and d_s is the reported mean diagonal length of the standard indentations.

15.2.2 The mean diagonal, $\bar{d}$, shall not differ from the mean diagonal, d_s, by more than 2 % or 0.5 μm, whichever is greater.

C. CALIBRATION OF STANDARDIZED HARDNESS TEST BLOCKS FOR MICROHARDNESS MACHINES

16. Scope

16.1 Part C covers the calibration of standardized hardness test blocks for the verification of microhardness testing machines as described in part B.

17. Manufacture

17.1 Each metal block to be standardized shall be not less than ¼ in. (6 mm) in thickness.

17.2 Each block shall be prepared to give the necessary repeatability.

17.3 Each block, if ferromagnetic, shall be demagnetized by the manufacturer and maintained in that condition by the user.

17.4 The supporting surface of the test block shall have a fine ground finish and the block shall be parallel to the test surface to ±0.0005 in./in. or ±1 min 40 s angular tolerance.

17.5 The test surface shall be polished and free from scratches that would interfere with measurements of the diagonals of the indentations.

17.5.1 The mean surface-roughness-height rating shall not exceed 4 μin. (0.001 μm), center-line average.

18. Standardizing Procedure

18.1 Calibrate the standardized hardness test blocks on a microhardness testing machine verified in accordance with the requirements of 13.1.

18.2 The mechanism that controls the application of load shall employ a device to maintain a constant velocity of the indenter.

18.3 Apply the full load for 10 to 15 s.

18.4 Make at least four groups, consisting of five indentations each, on each test block.

18.5 Adjust the illuminating system of the measuring microscope to give uniform intensity over the field of view and maximum contrast between the indentation and the undisturbed surface of the block (see 5.3.1.3 and Annex A1).

18.6 Check the measuring microscope with a stage micrometer, or by other suitable means, to ensure that the difference between readings corresponding to any two divisions of the instrument is correct within ±0.5 μm.

19. Repeatability

19.1 *Let* $d_1, d_2, \ldots, d_n$ be the mean values of the measured diagonals as determined by one observer, arranged in increasing order of magnitude.

19.2 The repeatability of the hardness readings on the blocks is expressed as $(d_{10} - d_1)$, when ten readings have been made, or 1.32 $(d_5 - d_1)$ when five readings are taken on the block.

19.3 Unless the repeatability of hardness readings as measured by the mean diagonals of five or ten indentations is within the limits given in Table 4, the block cannot be regarded as sufficiently uniform for standardization purposes.

20. Marking

20.1 Each block shall be marked with an appropriate identifying serial number.

21. Certification

21.1 The certificate accompanying each standardized hardness test block shall include:

21.1.1 Arithmetic mean of the hardness values found in the standardization test followed by the tolerance range for each group of five indentations.

21.1.2 Test load.

21.1.3 Serial number of test block.

21.1.4 Name of the certifying organization, and

21.1.5 Magnification.

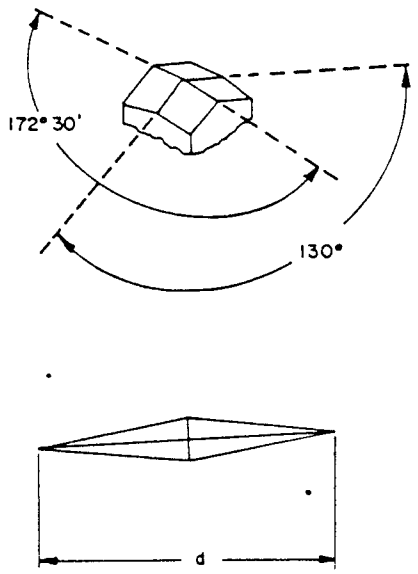


FIG. 1 Knoop Indenter

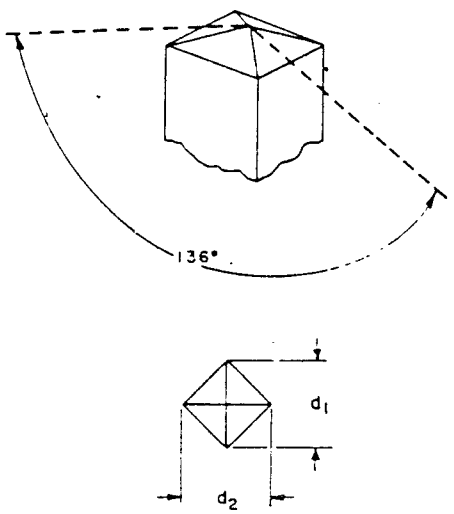


FIG. 2 Vickers Indenter

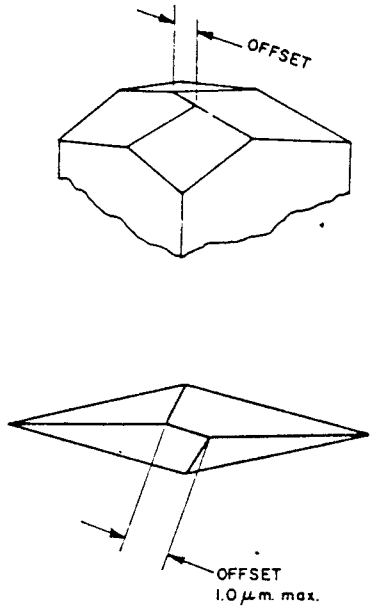


FIG. 3 Knoop Indenter Offset

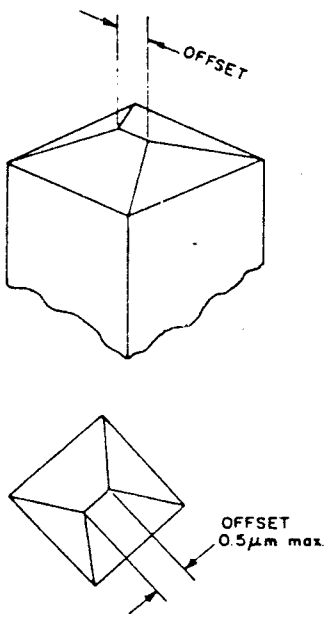


FIG. 4 Vickers Indenter Offset

TABLE 1 Knoop Hardness Numbers for Load of 1 gf

Diagonal of Impression, µm	Knoop Hardness Number for Diagonal Measured to 0.1 µm									
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1	14230	11760	9881	8420	7260	6324	5558	4924	4392	3942
2	3557	3227	2940	2690	2470	2277	2105	1952	1815	1692
3	1581	1481	1390	1307	1231	1162	1098	1039	985.4	935.5
4	889.3	846.5	806.6	769.5	735.0	702.7	672.4	644.1	617.6	592.6
5	569.2	547.1	526.2	506.2	488.0	470.4	453.7	437.9	423.0	408.8
6	395.2	382.4	370.2	358.5	347.4	336.8	326.7	317.0	307.7	298.9
7	290.4	282.3	274.5	267.0	259.8	253.0	246.3	240.0	233.9	228.0
8	222.3	216.9	211.6	206.5	201.7	196.9	192.4	188.0	183.7	179.6
9	175.7	171.8	168.1	164.5	161.0	157.7	154.4	151.2	148.2	145.2
10	142.3	139.5	136.8	134.1	131.6	129.1	126.6	124.3	122.0	119.8
11	117.6	115.5	113.4	111.4	109.5	107.6	105.7	103.9	102.2	100.5
12	98.81	97.19	95.60	94.05	92.54	91.07	89.63	88.22	86.85	85.51
13	84.20	82.91	81.66	80.44	79.24	78.07	76.93	75.81	74.72	73.65
14	72.60	71.57	70.57	69.58	68.62	67.68	66.75	65.85	64.96	64.09
15	63.24	62.40	61.59	60.78	60.00	59.23	58.47	57.73	57.00	56.28
16	55.58	54.89	54.22	53.55	52.90	52.26	51.64	51.02	50.41	49.82
17	49.24	48.66	48.10	47.54	47.00	46.46	45.94	45.42	44.91	44.41
18	43.92	43.43	42.96	42.49	42.03	41.57	41.13	40.69	40.26	39.83
19	39.42	39.00	38.60	38.20	37.81	37.42	37.04	36.66	36.29	35.93
20	35.57	35.22	34.87	34.53	34.19	33.86	33.53	33.21	32.89	32.57
21	32.27	31.96	31.66	31.36	31.07	30.78	30.50	30.22	29.94	29.67
22	29.40	29.13	28.87	28.61	28.36	28.11	27.86	27.61	27.37	27.13
23	26.90	26.67	26.44	26.21	25.99	25.77	25.55	25.33	25.12	24.91
24	24.70	24.50	24.30	24.10	23.90	23.71	23.51	23.32	23.14	22.95
25	22.77	22.59	22.41	22.23	22.05	21.88	21.71	21.54	21.38	21.21
26	21.05	20.89	20.73	20.57	20.42	20.26	20.11	19.96	19.81	19.66
27	19.52	19.37	19.23	19.09	18.95	18.82	18.68	18.54	18.41	18.28
28	18.15	18.02	17.23	17.77	17.64	17.52	17.40	17.27	17.15	17.04
29	16.92	16.80	16.89	16.57	16.46	16.35	16.24	16.13	16.01	15.92
30	15.81	15.71	15.60	15.60	15.40	15.30	15.20	15.10	15.00	14.90
31	14.81	14.71	14.62	14.52	14.43	14.34	14.25	14.16	14.07	13.98
32	13.90	13.81	13.72	13.64	13.55	13.47	13.39	13.31	13.23	13.15
33	13.07	12.99	12.91	12.83	12.75	12.68	12.60	12.53	12.45	12.38
34	12.31	12.24	12.17	12.09	12.02	11.95	11.89	11.82	11.75	11.68
35	11.62	11.55	11.48	11.42	11.35	11.29	11.23	11.16	11.10	11.04
36	10.98	10.92	10.86	10.80	10.74	10.68	10.62	10.56	10.51	10.45
37	10.39	10.34	10.28	10.23	10.17	10.12	10.06	10.01	9.958	9.906
38	9.854	9.802	9.751	9.700	9.650	9.600	9.550	9.501	9.452	9.403
39	9.355	9.307	9.260	9.213	9.166	9.120	9.074	9.028	8.983	8.938
40	8.893	8.849	8.805	8.761	8.718	8.675	8.632	8.590	8.548	8.506
41	8.465	8.423	8.383	8.342	8.302	8.262	8.222	8.183	8.144	8.105
42	8.066	8.028	7.990	7.952	7.915	7.878	7.841	7.804	7.768	7.731
43	7.695	7.660	7.624	7.589	7.554	7.520	7.485	7.451	7.417	7.383
44	7.350	7.316	7.283	7.250	7.218	7.185	7.153	7.121	7.090	7.058
45	7.027	6.996	6.965	6.934	6.903	6.873	6.843	6.813	6.783	6.754
46	6.724	6.695	6.666	6.638	6.609	6.581	6.552	6.524	6.497	6.469
47	6.441	6.414	6.387	6.360	6.333	6.306	6.280	6.254	6.228	6.202
48	6.176	6.150	6.125	6.099	6.074	6.049	6.024	6.000	5.975	5.951
49	5.926	5.902	5.878	5.854	5.831	5.807	5.784	5.761	5.737	5.714
50	5.692	5.669	5.646	5.624	5.602	5.579	5.557	5.536	5.514	5.492
51	5.471	5.449	5.428	5.407	5.386	5.365	5.344	5.323	5.303	5.282
52	5.262	5.242	5.222	5.202	5.182	5.162	5.143	5.123	5.104	5.085
53	5.065	5.046	5.027	5.009	4.990	4.971	4.953	4.934	4.916	4.898
54	4.880	4.082	4.844	4.826	4.808	4.790	4.773	4.756	4.738	4.721
55	4.704	4.687	4.670	4.653	4.636	4.619	4.603	4.586	4.570	4.554
56	4.537	4.521	4.505	4.489	4.473	4.457	4.442	4.426	4.410	4.395
57	4.379	4.364	4.349	4.334	4.319	4.304	4.289	4.274	4.259	4.244
58	4.230	4.215	4.201	4.188	4.172	4.158	4.144	4.129	4.115	4.102
59	4.088	4.074	4.060	4.046	4.033	4.019	4.006	3.992	3.070	3.966
60	3.952	3.939	3.926	3.913	3.900	3.887	3.875	3.862	3.849	3.837

TABLE 1 *Continued*

Diagonal of Impression, µm	Knoop Hardness Number for Diagonal Measured to 0.1 µm									
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
61	3.824	3.811	3.799	3.787	3.774	3.762	3.750	3.738	3.726	3.714
62	3.702	3.690	3.678	3.666	3.654	3.643	3.631	3.619	3.608	3.596
63	3.585	3.574	3.562	3.551	3.540	3.529	3.518	3.507	3.496	3.485
64	3.474	3.463	3.452	3.442	3.431	3.420	3.410	3.399	3.389	3.378
65	3.368	3.357	3.347	3.337	3.327	3.317	3.306	3.296	3.286	3.276
66	3.267	3.257	3.247	3.237	3.227	3.218	3.208	3.198	3.189	3.179
67	3.170	3.160	3.151	3.142	3.132	3.123	3.114	3.105	3.953	3.086
68	3.077	3.068	3.059	3.050	3.041	3.032	3.024	3.015	3.006	2.997
69	2.989	2.980	2.971	2.963	2.954	2.946	2.937	2.929	2.921	2.912
70	2.904	2.896	2.887	2.879	2.871	2.863	2.855	2.846	2.839	2.831
71	2.823	2.815	2.807	2.799	2.791	2.783	2.776	2.768	2.760	2.752
72	2.745	2.737	2.730	2.722	2.715	2.707	2.700	2.692	2.685	2.677
73	2.670	2.663	2.656	2.648	2.641	2.634	2.627	2.620	2.613	2.605
74	2.598	2.591	2.584	2.577	2.571	2.564	2.557	2.550	2.543	2.536
75	2.530	2.523	2.516	2.509	2.503	2.496	2.490	2.483	2.476	2.470
76	2.463	2.457	2.451	2.444	2.438	2.431	2.425	2.419	2.412	2.406
77	2.400	2.394	2.387	2.381	2.375	2.369	2.363	2.357	2.351	2.345
78	2.339	2.333	2.327	2.321	2.315	2.309	2.303	2.297	2.292	2.286
79	2.280	2.274	2.268	2.263	2.257	2.251	2.246	2.240	2.234	2.229
80	2.223	2.218	2.212	2.207	2.201	2.196	2.190	2.185	2.179	2.174
81	2.169	2.163	2.158	2.153	2.147	2.142	2.137	2.132	2.127	2.121
82	2.116	2.111	2.106	2.101	2.096	2.091	2.086	2.080	2.075	2.070
83	2.065	2.060	2.056	2.051	2.046	2.041	2.036	2.031	2.026	2.021
84	2.017	2.012	2.077	2.002	1.998	1.993	1.988	1.983	1.979	1.974
85	1.969	1.965	1.960	1.956	1.951	1.946	1.942	1.937	1.933	1.928
86	1.924	1.919	1.915	1.911	1.906	1.902	1.897	1.893	1.889	1.884
87	1.880	1.876	1.871	1.867	1.863	1.858	1.854	1.850	1.846	1.842
88	1.837	1.833	1.829	1.825	1.821	1.817	1.813	1.809	1.804	1.800
89	1.796	1.792	1.788	1.784	1.780	1.776	1.772	1.768	1.765	1.761
90	1.757	1.753	1.749	1.745	1.741	1.737	1.733	1.730	1.726	1.722
91	1.718	1.715	1.711	1.707	1.703	1.700	1.696	1.692	1.688	1.685
92	1.681	1.677	1.674	1.670	1.667	1.663	1.659	1.656	1.652	1.649
93	1.654	1.642	1.638	1.635	1.631	1.628	1.624	1.621	1.617	1.614
94	1.610	1.607	1.604	1.600	1.597	1.593	1.590	1.587	1.583	1.580
95	1.577	1.573	1.570	1.567	1.563	1.560	1.557	1.554	1.550	1.547
96	1.544	1.541	1.538	1.534	1.531	1.528	1.525	1.522	1.519	1.515
97	1.512	1.509	1.506	1.503	1.500	1.497	1.494	1.491	1.488	1.485
98	1.482	1.479	1.476	1.473	1.470	1.467	1.464	1.461	1.458	1.455
99	1.452	1.449	1.446	1.443	1.440	1.437	1.434	1.431	1.429	1.426
100	1.423	1.420	1.417	1.413	1.412	1.409	1.406	1.403	1.400	1.398
101	1.395	1.392	1.389	1.387	1.384	1.381	1.378	1.376	1.373	1.370
102	1.368	1.365	1.362	1.360	1.357	1.354	1.352	1.349	1.346	1.344
103	1.341	1.339	1.336	1.333	1.331	1.328	1.326	1.323	1.321	1.318
104	1.316	1.313	1.311	1.308	1.305	1.303	1.301	1.298	1.296	1.293
105	1.291	1.288	1.286	1.283	1.281	1.278	1.276	1.274	1.271	1.269
106	1.266	1.264	1.262	1.259	1.257	1.255	1.252	1.250	1.247	1.245
107	1.243	1.240	1.238	1.236	1.234	1.231	1.229	1.227	1.224	1.222
108	1.220	1.218	1.215	1.213	1.211	1.209	1.206	1.204	1.202	1.200
109	1.198	1.195	1.193	1.191	1.189	1.187	1.185	1.182	1.180	1.178
110	1.176	1.174	1.172	1.170	1.167	1.165	1.163	1.161	1.159	1.157
111	1.155	1.153	1.151	1.149	1.147	1.145	1.142	1.140	1.138	1.136
112	1.134	1.132	1.130	1.128	1.126	1.124	1.122	1.120	1.118	1.116
113	1.114	1.112	1.110	1.108	1.106	1.105	1.103	1.101	1.099	1.097
114	1.095	1.093	1.091	1.089	1.087	1.085	1.083	1.082	1.080	1.078
115	1.076	1.074	1.072	1.070	1.068	1.067	1.065	1.063	1.161	1.059
116	1.057	1.056	1.054	1.052	1.050	1.048	1.047	1.045	1.043	1.041
117	1.039	1.038	1.036	1.034	1.032	1.031	1.029	1.027	1.025	1.024
118	1.022	1.020	1.018	1.017	1.015	1.013	1.012	1.010	1.008	1.006
119	1.005	1.003	1.001	0.9998	0.9981	0.9964	0.9947	0.9931	0.9914	0.9898
120	0.9881	0.9865	0.9848	0.9832	0.9816	0.9799	0.9783	0.9767	0.9751	0.9735

TABLE 1 *Continued*

Diagonal of Impression, µm	Knoop Hardness Number for Diagonal Measured to 0.1 µm									
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
121	0.9719	0.9703	0.9687	0.9671	0.9655	0.9639	0.9623	0.9607	0.9591	0.9576
122	0.9560	0.9544	0.9529	0.9513	0.9498	0.9482	0.9467	0.9451	0.9436	0.9420
123	0.9405	0.9390	0.9375	0.9359	0.9344	0.9329	0.9314	0.9299	0.9284	0.9269
124	0.9254	0.9239	0.9224	0.9209	0.9195	0.9180	0.9165	0.9150	0.9136	0.9121
125	0.9107	0.9092	0.9078	0.9063	0.9049	0.9034	0.9020	0.9005	0.8991	0.8977
126	0.8963	0.8948	0.8934	0.8920	0.8906	0.8892	0.8878	0.8864	0.8850	0.8836
127	0.8822	0.8808	0.8794	0.8780	0.8767	0.8753	0.8739	0.8726	0.8712	0.8698
128	0.8685	0.8671	0.8658	0.8644	0.8631	0.8617	0.8604	0.8591	0.8577	0.8564
129	0.8551	0.8537	0.8524	0.8511	0.8498	0.8485	0.8472	0.8459	0.8446	0.8433
130	0.8420	0.8407	0.8394	0.8381	0.8368	0.8355	0.8343	0.8330	0.8317	0.8304
131	0.8291	0.8279	0.8266	0.8254	0.8241	0.8229	0.8216	0.8204	0.8191	0.8179
132	0.8166	0.8154	0.8142	0.8129	0.8117	0.8105	0.8093	0.8080	0.8068	0.8056
133	0.8044	0.8032	0.8020	0.8008	0.7996	0.7984	0.7972	0.7960	0.7948	0.7936
134	0.7924	0.7913	0.7901	0.7889	0.7877	0.7866	0.7854	0.7842	0.7831	0.7819
135	0.7807	0.7796	0.7784	0.7773	0.7761	0.7750	0.7738	0.7727	0.7716	0.7704
136	0.7693	0.7682	0.7670	0.7659	0.7648	0.7637	0.7626	0.7614	0.7603	0.7592
137	0.7581	0.7570	0.7559	0.7548	0.7537	0.7526	0.7515	0.7504	0.7493	0.7483
138	0.7472	0.7461	0.7450	0.7439	0.7429	0.7418	0.7407	0.7396	0.7386	0.7375
139	0.7365	0.7354	0.7343	0.7333	0.7322	0.7312	0.7301	0.7291	0.7281	0.7270
140	0.7260	0.7249	0.7239	0.7229	0.7218	0.7208	0.7198	0.7188	0.7177	0.7167
141	0.7157	0.7147	0.7137	0.7127	0.7117	0.7107	0.7097	0.7087	0.7077	0.7067
142	0.7057	0.7047	0.7037	0.7027	0.7017	0.7007	0.6997	0.6988	0.6978	0.6968
143	0.6958	0.6949	0.6939	0.6929	0.6920	0.6910	0.6900	0.6891	0.6881	0.6872
144	0.6862	0.6852	0.6843	0.6834	0.6824	0.6815	0.6805	0.6796	0.6786	0.6777
145	0.6768	0.6758	0.6749	0.6740	0.6731	0.6721	0.6712	0.6703	0.6694	0.6684
146	0.6675	0.6666	0.6657	0.6648	0.6639	0.6630	0.6621	0.6612	0.6603	0.6594
147	0.6585	0.6576	0.6567	0.6558	0.6549	0.6540	0.6531	0.6523	0.6514	0.6505
148	0.6496	0.6487	0.6479	0.6470	0.6461	0.6452	0.6444	0.6435	0.6426	0.6418
149	0.6409	0.6401	0.6392	0.6383	0.6375	0.6366	0.6358	0.6349	0.6341	0.6332
150	0.6324	0.6316	0.6307	0.6299	0.6290	0.6282	0.6274	0.6265	0.6257	0.6249
151	0.6241	0.6232	0.6224	0.6216	0.6208	0.6199	0.6191	0.6183	0.6175	0.6167
152	0.6159	0.6151	0.6143	0.6134	0.6126	0.6118	0.6110	0.6102	0.6094	0.6086
153	0.6078	0.6071	0.6063	0.6055	0.6047	0.6039	0.6031	0.6023	0.6015	0.6008
154	0.6000	0.5992	0.5984	0.5976	0.5969	0.5961	0.5953	0.5946	0.5938	0.5930
155	0.5923	0.5915	0.5907	0.5900	0.5892	0.5885	0.5877	0.5869	0.5862	0.5854
156	0.5847	0.5839	0.5832	0.5825	0.5817	0.5810	0.5802	0.5795	0.5787	0.5780
157	0.5773	0.5765	0.5758	0.5751	0.5743	0.5736	0.5729	0.5722	0.5714	0.5707
158	0.5700	0.5693	0.5685	0.5678	0.5671	0.5664	0.5657	0.5650	0.5643	0.5635
159	0.5628	0.5621	0.5614	0.5607	0.5600	0.5593	0.5586	0.5579	0.5572	0.5565
160	0.5558	0.5551	0.5544	0.5537	0.5531	0.5524	0.5517	0.5510	0.5503	0.5496
161	0.5489	0.5483	0.5476	0.5469	0.5462	0.5455	0.5449	0.5442	0.5435	0.5429
162	0.5422	0.5415	0.5408	0.5402	0.5395	0.5389	0.5382	0.5375	0.5369	0.5362
163	0.5356	0.5349	0.5342	0.5336	0.5329	0.5323	0.5316	0.5310	0.5303	0.5297
164	0.5290	0.5284	0.5278	0.5271	0.5265	0.5258	0.5252	0.5246	0.5239	0.5233
165	0.5226	0.5220	0.5214	0.5208	0.5201	0.5195	0.5189	0.5182	0.5176	0.5170
166	0.5164	0.5157	0.5151	0.5145	0.5139	0.5133	0.5127	0.5120	0.5114	0.5108
167	0.5102	0.5096	0.5090	0.5084	0.5078	0.5072	0.5066	0.5060	0.5054	0.5047
168	0.5041	0.5035	0.5030	0.5024	0.5018	0.5012	0.5006	0.5000	0.4994	0.4988
169	0.4982	0.4976	0.4970	0.4964	0.4959	0.4953	0.4947	0.4941	0.4935	0.4929
170	0.4924	0.4918	0.4912	0.4906	0.4900	0.4895	0.4889	0.4883	0.4878	0.4872
171	0.4866	0.4860	0.4855	0.4849	0.4843	0.4838	0.4832	0.4827	0.4821	0.4815
172	0.4810	0.4804	0.4799	0.4793	0.4787	0.4782	0.4776	0.4771	0.4765	0.4760
173	0.4754	0.4749	0.4743	0.4738	0.4732	0.4727	0.4721	0.4716	0.4711	0.4705
174	0.4700	0.4694	0.4689	0.4684	0.4678	0.4673	0.4668	0.4662	0.4657	0.4652
175	0.4646	0.4641	0.4636	0.4630	0.4625	0.4620	0.4615	0.4609	0.4604	0.4599
176	0.4594	0.4588	0.4583	0.4578	0.4573	0.4568	0.4562	0.4557	0.4552	0.4547
177	0.4542	0.4537	0.4532	0.4526	0.4521	0.4516	0.4511	0.4506	0.4501	0.4496
178	0.4491	0.4486	0.4481	0.4476	0.4471	0.4466	0.4461	0.4456	0.4451	0.4446
179	0.4441	0.4436	0.4431	0.4426	0.4421	0.4416	0.4411	0.4406	0.4401	0.4397
180	0.4392	0.4387	0.4382	0.4377	0.4372	0.4367	0.4363	0.4358	0.4353	0.4348

TABLE 1 *Continued*

Diagonal of Impression, µm	Knoop Hardness Number for Diagonal Measured to 0.1 µm									
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
181	0.4343	0.4339	0.4334	0.4329	0.4324	0.4319	0.4315	0.4310	0.4305	0.4300
182	0.4296	0.4291	0.4286	0.4282	0.4277	0.4272	0.4268	0.4263	0.4258	0.4254
183	0.4249	0.4244	0.4240	0.4235	0.4230	0.4226	0.4221	0.4217	0.4212	0.4207
184	0.4203	0.4198	0.4194	0.4189	0.4185	0.4180	0.4176	0.4171	0.4167	0.4162
185	0.4158	0.4153	0.4149	0.4144	0.4140	0.4135	0.4131	0.4126	0.4122	0.4117
186	0.4113	0.4109	0.4104	0.4100	0.4095	0.4091	0.4087	0.4082	0.4078	0.4073
187	0.4069	0.4065	0.4060	0.4056	0.4052	0.4047	0.4043	0.4039	0.4034	0.4030
188	0.4026	0.4022	0.4017	0.4013	0.4009	0.4005	0.4000	0.3996	0.3992	0.3988
189	0.3983	0.3979	0.3975	0.3971	0.3967	0.3962	0.3958	0.3954	0.3950	0.3946
190	0.3942	0.3937	0.3933	0.3929	0.3925	0.3921	0.3917	0.3913	0.3909	0.3905
191	0.3900	0.3896	0.3892	0.3888	0.3884	0.3880	0.3876	0.3872	0.3868	0.3864
192	0.3860	0.3856	0.3852	0.3848	0.3844	0.3840	0.3836	0.3832	0.3828	0.3824
193	0.3820	0.3816	0.3812	0.3808	0.3804	0.3800	0.3796	0.3792	0.3789	0.3785
194	0.3781	0.3777	0.3773	0.3769	0.3765	0.3761	0.3757	0.3754	0.3750	0.3746
195	0.3742	0.3738	0.3734	0.3731	0.3727	0.3723	0.3719	0.3715	0.3712	0.3708
196	0.3704	0.3700	0.3696	0.3693	0.3689	0.3685	0.3681	0.3678	0.3674	0.3670
197	0.3663	0.3663	0.3659	0.3655	0.3652	0.3648	0.3644	0.3641	0.3637	0.3633
198	0.3630	0.3626	0.3622	0.3619	0.3615	0.3611	0.3608	0.3604	0.3600	0.3597
199	0.3593	0.3590	0.3586	0.3582	0.3579	0.3575	0.3572	0.3568	0.3564	0.3561
200	0.3557	0.3554	0.3550	0.3547	0.3543	0.3540	0.3536	0.3533	0.3529	0.3525

TABLE 2 Vickers Hardness Numbers for Load of 1 gf

Diagonal of Impression, µm	Vickers Hardness Number for Diagonal Measured to 0.1 µm									
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1	1854.6	1533.5	1288.1	1097.5	946.1	824.2	724.4	641.6	572.3	513.7
2	463.0	420.0	383.1	350.3	321.9	296.7	274.3	254.4	236.5	220.5
3	206.9	193.3	181.1	170.3	160.4	151.4	143.1	135.5	128.4	121.9
4	115.17	110.29	105.58	100.01	95.78	91.57	87.64	83.95	80.48	77.23
5	74	71	68	66	63.59	61.30	59.13	57.07	55.12	53.27
6	51.51	49.83	48.24	46.72	45.27	43.89	42.57	41.31	40.10	38.95
7	37.84	36.79	35.77	34.80	33.86	32.97	32.10	31.28	30.48	29.71
8	28.97	28.26	27.58	26.92	26.28	25.67	25.07	24.50	23.95	23.41
9	22.89	22.39	21.91	21.44	20.99	20.55	20.12	19.71	19.31	18.92
10	18.54	18.18	17.82	17.48	17.14	16.82	16.50	16.20	15.90	15.61
11	15.33	15.05	14.78	14.52	14.27	14.02	13.78	13.55	13.32	13.09
12	12.88	12.67	12.46	12.26	12.06	11.87	11.68	11.50	11.32	11.14
13	10.97	10.81	10.64	10.48	10.33	10.17	10.03	9.880	9.737	9.598
14	9.461	9.327	9.196	9.068	8.943	8.820	8.699	8.581	8.466	8.353
15	8.242	8.133	8.026	7.922	7.819	7.718	7.620	7.523	7.428	7.335
16	7.244	7.154	7.066	6.979	6.895	6.811	6.729	6.649	6.570	6.493
17	6.416	6.342	6.268	6.196	6.125	6.055	5.986	5.919	5.853	5.787
18	5.723	5.660	5.598	5.537	5.477	5.418	5.360	5.303	5.247	5.191
19	5.137	5.083	5.030	4.978	4.927	4.877	4.827	4.778	4.730	4.683
20	4.636	4.590	4.545	4.500	4.456	4.413	4.370	4.328	4.286	4.245
21	4.205	4.165	4.126	4.087	4.049	4.012	3.975	3.938	3.902	3.866
22	3.831	3.797	3.763	3.729	3.696	3.663	3.631	3.599	3.587	3.536
23	3.505	3.475	3.445	3.416	3.387	3.358	3.329	3.301	3.274	3.246
24	3.219	3.193	3.166	3.140	3.115	3.089	3.064	3.039	3.015	2.991
25	2.967	2.943	2.920	2.897	2.874	2.852	2.830	2.808	2.786	2.764
26	2.743	2.722	2.701	2.681	2.661	2.641	2.621	2.601	2.582	2.563
27	2.544	2.525	2.506	2.488	2.470	2.452	2.434	2.417	2.399	2.382
28	2.365	2.348	2.332	2.315	2.299	2.283	2.267	2.251	2.236	2.220
29	2.205	2.190	2.175	2.160	2.145	2.131	2.116	2.102	2.088	2.074
30	2.060	2.047	2.033	2.020	2.007	1.993	1.980	1.968	1.955	1.942
31	1.930	1.917	1.905	1.893	1.881	1.869	1.857	1.845	1.834	1.822
32	1.811	1.800	1.788	1.777	1.766	1.756	1.745	1.734	1.724	1.713
33	1.703	1.693	1.682	1.672	1.662	1.652	1.643	1.633	1.623	1.614
34	1.604	1.595	1.585	1.576	1.567	1.558	1.549	1.540	1.531	1.522
35	1.514	1.505	1.497	1.488	1.480	1.471	1.463	1.455	1.447	1.439
36	1.431	1.423	1.415	1.407	1.400	1.392	1.384	1.377	1.369	1.362
37	1.355	1.347	1.340	1.333	1.326	1.319	1.312	1.305	1.298	1.291
38	1.284	1.277	1.271	1.264	1.258	1.251	1.245	1.238	1.232	1.225
39	1.219	1.213	1.207	1.201	1.195	1.189	1.183	1.177	1.171	1.165
40	1.159	1.153	1.147	1.142	1.136	1.131	1.125	1.119	1.114	1.109
41	1.103	1.098	1.092	1.087	1.082	1.077	1.072	1.066	1.061	1.056
42	1.051	1.046	1.041	1.036	1.031	1.027	1.022	1.017	1.012	1.008
43	0.003	0.9983	0.9936	0.9891	0.9845	0.9800	0.9755	0.9710	0.9666	0.9622
44	0.9578	0.9535	0.9492	0.9449	0.9407	0.9364	0.9322	0.9281	0.9239	0.9198
45	0.9157	0.9117	0.9077	0.9036	0.8997	0.8957	0.8918	0.8879	0.8840	0.8802
46	0.8764	0.8726	0.8688	0.8650	0.8613	0.8576	0.8539	0.8503	0.8467	0.8430
47	0.8395	0.8359	0.8324	0.8288	0.8254	0.8219	0.8184	0.8150	0.8116	0.8082
48	0.8048	0.8015	0.7982	0.7949	0.7916	0.7883	0.7851	0.7819	0.7787	0.7755
49	0.7723	0.7692	0.7661	0.7630	0.7599	0.7568	0.7538	0.7507	0.7477	0.7447
50	0.7417	0.7388	0.7359	0.7329	0.7300	0.7271	0.7243	0.7214	0.7186	0.7158
51	0.7129	0.7102	0.7074	0.7046	0.7019	0.6992	0.6965	0.6938	0.6911	0.6884
52	0.6858	0.6832	0.6805	0.6779	0.6754	0.6728	0.6702	0.6677	0.6652	0.6627
53	0.6602	0.6577	0.6552	0.6527	0.6503	0.6479	0.6455	0.6431	0.6407	0.6383
54	0.6359	0.6336	0.6312	0.6289	0.6266	0.6243	0.6220	0.6198	0.6175	0.6153
55	0.6130	0.6108	0.6086	0.6064	0.6042	0.6020	0.5999	0.5977	0.5956	0.5934
56	0.5913	0.5892	0.5871	0.5850	0.5830	0.5809	0.5788	0.5768	0.5748	0.5728
57	0.5708	0.5688	0.5668	0.5648	0.5628	0.5609	0.5589	0.5570	0.5551	0.5531
58	0.5512	0.5493	0.5475	0.5456	0.5437	0.5419	0.5400	0.5382	0.5363	0.5345
59	0.5327	0.5309	0.5291	0.5273	0.5256	0.5238	0.5220	0.5203	0.5186	0.5168
60	0.5151	0.5134	0.5117	0.5100	0.5083	0.5066	0.5050	0.5033	0.5016	0.5000

TABLE 2 *Continued*

Diagonal of Impression, µm	Vickers Hardness Number for Diagonal Measured to 0.1 µm									
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
61	0.4984	0.4967	0.4951	0.4935	0.4919	0.4903	0.4887	0.4871	0.4855	0.4840
62	0.4824	0.4809	0.4793	0.4778	0.4762	0.4747	0.4732	0.4717	0.4702	0.4687
63	0.4672	0.4657	0.4643	0.4628	0.4613	0.4599	0.4584	0.4570	0.4556	0.4541
64	0.4527	0.4513	0.4499	0.4485	0.4471	0.4457	0.4444	0.4430	0.4416	0.4403
65	0.4389	0.4376	0.4362	0.4349	0.4336	0.4322	0.4309	0.4296	0.4283	0.4270
66	0.4257	0.4244	0.4231	0.4219	0.4206	0.4193	0.4181	0.4168	0.4156	0.4143
67	0.4131	0.4119	0.4106	0.4094	0.4082	0.4070	0.4058	0.4046	0.4034	0.4022
68	0.4010	0.3999	0.3987	0.3975	0.3964	0.3952	0.3941	0.3929	0.3918	0.3906
69	0.3895	0.3884	0.3872	0.3861	0.3850	0.3839	0.3828	0.3817	0.3806	0.3795
70	0.3784	0.3774	0.3763	0.3752	0.3742	0.3731	0.3720	0.3710	0.3699	0.3689
71	0.3679	0.3668	0.3658	0.3648	0.3638	0.3627	0.3617	0.3607	0.3597	0.3587
72	0.3577	0.3567	0.3557	0.3548	0.3538	0.3528	0.3518	0.3509	0.3499	0.3489
73	0.3480	0.3470	0.3461	0.3451	0.3442	0.3433	0.3423	0.3414	0.3405	0.3396
74	0.3386	0.3377	0.3368	0.3359	0.3350	0.3341	0.3332	0.3323	0.3314	0.3305
75	0.3297	0.3288	0.3279	0.3270	0.3262	0.3253	0.3245	0.3236	0.3227	0.3219
76	0.3211	0.3202	0.3194	0.3185	0.3177	0.3169	0.3160	0.3152	0.3144	0.3136
77	0.3128	0.3120	0.3111	0.3103	0.3095	0.3087	0.3079	0.3072	0.3064	0.3056
78	0.3048	0.3040	0.3032	0.3025	0.3017	0.3009	0.3002	0.2994	0.2986	0.2979
79	0.2971	0.2964	0.2956	0.2949	0.2941	0.2934	0.2927	0.2919	0.2912	0.2905
80	0.2897	0.2890	0.2883	0.2876	0.2869	0.2862	0.2855	0.2847	0.2840	0.2833
81	0.2826	0.2819	0.2812	0.2806	0.2799	0.2792	0.2785	0.2778	0.2771	0.2765
82	0.2758	0.2751	0.2744	0.2738	0.2731	0.2725	0.2718	0.2711	0.2705	0.2698
83	0.2692	0.2685	0.2697	0.2672	0.2666	0.2660	0.2653	0.2647	0.2641	0.2634
84	0.2628	0.2622	0.2616	0.2609	0.2603	0.2597	0.2591	0.2585	0.2579	0.2573
85	0.2567	0.2561	0.2555	0.2549	0.2543	0.2537	0.2531	0.2525	0.2519	0.2513
86	0.2507	0.2501	0.2496	0.2490	0.2484	0.2478	0.2473	0.2467	0.2461	0.2456
87	0.2450	0.2444	0.2439	0.2433	0.2428	0.2422	0.2417	0.2411	0.2406	0.2400
88	0.2395	0.2389	0.2384	0.2378	0.2373	0.2368	0.2362	0.2357	0.2352	0.2346
89	0.2341	0.2336	0.2331	0.2325	0.2320	0.2315	0.2310	0.2305	0.2300	0.2294
90	0.2289	0.2284	0.2279	0.2274	0.2269	0.2264	0.2259	0.2254	0.2249	0.2244
91	0.2239	0.2234	0.2230	0.2225	0.2220	0.2215	0.2210	0.2205	0.2200	0.2196
92	0.2191	0.2186	0.2181	0.2177	0.2172	0.2167	0.2163	0.2158	0.2153	0.2149
93	0.2144	0.2139	0.2135	0.2130	0.2126	0.2121	0.2117	0.2112	0.2108	0.2103
94	0.2099	0.2094	0.2090	0.2085	0.2081	0.2077	0.2072	0.2068	0.2063	0.2059
95	0.2055	0.2050	0.2046	0.2042	0.2038	0.2033	0.2029	0.2025	0.2021	0.2016
96	0.2012	0.2008	0.2004	0.2000	0.1995	0.1991	0.1987	0.1983	0.1979	0.1975
97	0.1971	0.1967	0.1963	0.1959	0.1955	0.1951	0.1947	0.1943	0.1939	0.1935
98	0.1931	0.1927	0.1923	0.1919	0.1915	0.1911	0.1907	0.1904	0.1900	0.1896
99	0.1892	0.1888	0.1884	0.1881	0.1877	0.1873	0.1869	0.1866	0.1862	0.1858
100	0.1854	0.1851	0.1847	0.1843	0.1840	0.1836	0.1832	0.1829	0.1825	0.1821
101	0.1818	0.1814	0.1811	0.1807	0.1804	0.1800	0.1796	0.1793	0.1789	0.1786
102	0.1782	0.1779	0.1775	0.1772	0.1769	0.1765	0.1762	0.1758	0.1755	0.1751
103	0.1748	0.1745	0.1741	0.1738	0.1734	0.1731	0.1728	0.1724	0.1721	0.1718
104	0.1715	0.1711	0.1708	0.1705	0.1701	0.1698	0.1695	0.1692	0.1688	0.1685
105	0.1682	0.1679	0.1676	0.1672	0.1669	0.1666	0.1663	0.1660	0.1657	0.1654
106	0.1650	0.1647	0.1644	0.1641	0.1638	0.1635	0.1632	0.1629	0.1626	0.1623
107	0.1620	0.1617	0.1614	0.1611	0.1608	0.1605	0.1602	0.1599	0.1596	0.1593
108	0.1590	0.1587	0.1584	0.1581	0.1578	0.1575	0.1572	0.1569	0.1567	0.1564
109	0.1561	0.1556	0.1555	0.1552	0.1549	0.1547	0.1544	0.1541	0.1538	0.1535
110	0.1533	0.1530	0.1527	0.1524	0.1521	0.1519	0.1516	0.1513	0.1511	0.1508
111	0.1505	0.1502	0.1500	0.1497	0.1494	0.1492	0.1489	0.1486	0.1484	0.1481
112	0.1478	0.1476	0.1473	0.1470	0.1468	0.1465	0.1463	0.1460	0.1457	0.1455
113	0.1452	0.1450	0.1447	0.1445	0.1442	0.1440	0.1437	0.1434	0.1432	0.1429
114	0.1427	0.1424	0.1422	0.1419	0.1417	0.1414	0.1412	0.1410	0.1407	0.1405
115	0.1402	0.1400	0.1397	0.1395	0.1393	0.1390	0.1388	0.1385	0.1383	0.1381
116	0.1378	0.1376	0.1373	0.1371	0.1369	0.1366	0.1364	0.1362	0.1359	0.1357
117	0.1355	0.1352	0.1350	0.1348	0.1345	0.1343	0.1341	0.1339	0.1336	0.1334
118	0.1332	0.1330	0.1327	0.1325	0.1323	0.1321	0.1318	0.1316	0.1314	0.1312
119	0.1310	0.1307	0.1305	0.1303	0.1301	0.1299	0.1296	0.1294	0.1292	0.1290
120	0.1288	0.1286	0.1284	0.1281	0.1279	0.1277	0.1275	0.1273	0.1271	0.1269

TABLE 2 *Continued*

Diagonal of Impression, µm	Vickers Hardness Number for Diagonal Measured to 0.1 µm									
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
121	0.1267	0.1265	0.1262	0.1260	0.1258	0.1256	0.1254	0.1252	0.1250	0.1248
122	0.1246	0.1244	0.1242	0.1240	0.1238	0.1236	0.1234	0.1232	0.1230	0.1228
123	0.1226	0.1224	0.1222	0.1220	0.1218	0.1216	0.1214	0.1212	0.1210	0.1208
124	0.1206	0.1204	0.1202	0.1200	0.1198	0.1196	0.1194	0.1193	0.1191	0.1189
125	0.1187	0.1185	0.1183	0.1181	0.1179	0.1177	0.1176	0.1174	0.1172	0.1170
126	0.1168	0.1166	0.1164	0.1163	0.1161	0.1159	0.1157	0.1155	0.1153	0.1152
127	0.1150	0.1148	0.1146	0.1144	0.1143	0.1141	0.1139	0.1137	0.1135	0.1134
128	0.1132	0.1130	0.1128	0.1127	0.1125	0.1123	0.1121	0.1120	0.1118	0.1116
129	0.1114	0.1113	0.1111	0.1109	0.1108	0.1106	0.1104	0.1102	0.1101	0.1099
130	0.1097	0.1096	0.1094	0.1092	0.1091	0.1089	0.1087	0.1086	0.1084	0.1082
131	0.1081	0.1079	0.1077	0.1076	0.1074	0.1072	0.1071	0.1069	0.1068	0.1066
132	0.1064	0.1063	0.1061	0.1059	0.1058	0.1056	0.1055	0.1053	0.1052	0.1050
133	0.1048	0.1047	0.1045	0.1044	0.1042	0.1041	0.1039	0.1037	0.1036	0.1034
134	0.1033	0.1031	0.1030	0.1028	0.1027	0.1025	0.1024	0.1022	0.1021	0.1019
135	0.1018	0.1016	0.1015	0.1013	0.1012	0.1010	0.1009	0.1007	0.1006	0.1004
136	0.1003	0.1001	0.1000	0.0998	0.0997	0.0995	0.0994	0.0992	0.0991	0.0989
137	0.0988	0.0987	0.0985	0.0984	0.0982	0.0981	0.0979	0.0978	0.0977	0.0975
138	0.0974	0.0972	0.0971	0.0970	0.0968	0.0967	0.0965	0.0964	0.0963	0.0961
139	0.0960	0.0958	0.0957	0.0956	0.0954	0.0953	0.0952	0.0950	0.0949	0.0948
140	0.0946	0.0945	0.0943	0.0942	0.0941	0.0939	0.0938	0.0937	0.0935	0.0934
141	0.0933	0.0931	0.0930	0.0929	0.0928	0.0926	0.0925	0.0924	0.0922	0.0921
142	0.0920	0.0918	0.0917	0.0916	0.0915	0.0913	0.0912	0.0911	0.0909	0.0908
143	0.0907	0.0906	0.0904	0.0903	0.0902	0.0901	0.0899	0.0898	0.0897	0.0896
144	0.0894	0.0893	0.0892	0.0891	0.0889	0.0888	0.0887	0.0886	0.0884	0.0883
145	0.0882	0.0881	0.0880	0.0878	0.0877	0.0876	0.0875	0.0874	0.0872	0.0871
146	0.0870	0.0869	0.0868	0.0866	0.0865	0.0864	0.0863	0.0862	0.0861	0.0859
147	0.0858	0.0857	0.0856	0.0855	0.0854	0.0852	0.0851	0.0850	0.0849	0.0848
148	0.0847	0.0845	0.0844	0.0843	0.0842	0.0841	0.0840	0.0839	0.0838	0.0836
149	0.0835	0.0834	0.0833	0.0832	0.0831	0.0830	0.0829	0.0828	0.0826	0.0825
150	0.0824	0.0823	0.0822	0.0821	0.0820	0.0819	0.0818	0.0817	0.0815	0.0814
151	0.0813	0.0812	0.0811	0.0810	0.0809	0.0808	0.0807	0.0806	0.0805	0.0804
152	0.0803	0.0802	0.0801	0.0800	0.0798	0.0797	0.0796	0.0795	0.0794	0.0793
153	0.0792	0.0791	0.0790	0.0789	0.0788	0.0787	0.0786	0.0785	0.0784	0.0783
154	0.0782	0.0781	0.0780	0.0779	0.0778	0.0777	0.0776	0.0775	0.0774	0.0773
155	0.0772	0.0771	0.0770	0.0769	0.0768	0.0767	0.0766	0.0765	0.0764	0.0763
156	0.0762	0.0761	0.0760	0.0759	0.0758	0.0757	0.0756	0.0755	0.0754	0.0753
157	0.0752	0.0751	0.0750	0.0749	0.0749	0.0748	0.0747	0.0746	0.0745	0.0744
158	0.0743	0.0742	0.0741	0.0740	0.0739	0.0738	0.0737	0.0736	0.0735	0.0734
159	0.0734	0.0733	0.0732	0.0731	0.0730	0.0729	0.0728	0.0727	0.0726	0.0725
160	0.0724	0.0724	0.0723	0.0722	0.0721	0.0720	0.0719	0.0718	0.0717	0.0716
161	0.0715	0.0715	0.0714	0.0713	0.0712	0.0711	0.0710	0.0709	0.0708	0.0708
162	0.0707	0.0706	0.0705	0.0704	0.0703	0.0702	0.0701	0.0701	0.0700	0.0699
163	0.0698	0.0697	0.0696	0.0695	0.0695	0.0694	0.0693	0.0692	0.0691	0.0690
164	0.0690	0.0689	0.0688	0.0687	0.0686	0.0685	0.0684	0.0684	0.0683	0.0682
165	0.0681	0.0680	0.0680	0.0679	0.0678	0.0677	0.0676	0.0675	0.0675	0.0674
166	0.0673	0.0672	0.0671	0.0671	0.0670	0.0669	0.0668	0.0667	0.0667	0.0666
167	0.0665	0.0664	0.0663	0.0663	0.0662	0.0661	0.0660	0.0659	0.0659	0.0658
168	0.0657	0.0656	0.0656	0.0655	0.0654	0.0653	0.0652	0.0652	0.0651	0.0650
169	0.0649	0.0649	0.0648	0.0647	0.0646	0.0645	0.0645	0.0644	0.0643	0.0642
170	0.0642	0.0641	0.0640	0.0639	0.0639	0.0638	0.0637	0.0636	0.0636	0.0635
171	0.0634	0.0633	0.0633	0.0632	0.0631	0.0631	0.0630	0.0629	0.0628	0.0628
172	0.0627	0.0626	0.0625	0.0625	0.0624	0.0623	0.0623	0.0622	0.0621	0.0620
173	0.0620	0.0619	0.0618	0.0617	0.0617	0.0616	0.0615	0.0615	0.0614	0.0613
174	0.0613	0.0612	0.0611	0.0610	0.0610	0.0609	0.0608	0.0608	0.0607	0.0606
175	0.0606	0.0605	0.0604	0.0603	0.0603	0.0602	0.0601	0.0601	0.0600	0.0559
176	0.0599	0.0598	0.0597	0.0597	0.0596	0.0595	0.0595	0.0594	0.0593	0.0593
177	0.0592	0.0591	0.0591	0.0590	0.0589	0.0589	0.0588	0.0587	0.0587	0.0586
178	0.0585	0.0585	0.0584	0.0583	0.0583	0.0582	0.0581	0.0581	0.0580	0.0579
179	0.0579	0.0578	0.0578	0.0577	0.0576	0.0576	0.0575	0.0574	0.0574	0.0573
180	0.0572	0.0572	0.0571	0.0570	0.0570	0.0569	0.0569	0.0568	0.0567	0.0567

TABLE 2 *Continued*

Diagonal of Impression, µm	Vickers Hardness Number for Diagonal Measured to 0.1 µm									
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
181	0.0566	0.0565	0.0565	0.0564	0.0564	0.0563	0.0562	0.0562	0.0561	0.0560
182	0.0560	0.0559	0.0559	0.0558	0.0557	0.0557	0.0556	0.0556	0.0555	0.0554
183	0.0554	0.0553	0.0553	0.0552	0.0551	0.0551	0.0550	0.0550	0.0549	0.0548
184	0.0548	0.0547	0.0547	0.0546	0.0545	0.0545	0.0544	0.0544	0.0543	0.0542
185	0.0542	0.0541	0.0541	0.0540	0.0540	0.0539	0.0538	0.0538	0.0537	0.0537
186	0.0536	0.0535	0.0535	0.0534	0.0534	0.0533	0.0533	0.0532	0.0531	0.0531
187	0.0530	0.0530	0.0529	0.0529	0.0528	0.0528	0.0527	0.0526	0.0526	0.0525
188	0.0525	0.0524	0.0524	0.0523	0.0522	0.0522	0.0521	0.0521	0.0520	0.0520
189	0.0519	0.0519	0.0518	0.0518	0.0517	0.0516	0.0516	0.0515	0.0515	0.0514
190	0.0514	0.0513	0.0513	0.0512	0.0512	0.0511	0.0510	0.0510	0.0509	0.0509
191	0.0508	0.0508	0.0507	0.0507	0.0506	0.0506	0.0505	0.0505	0.0504	0.0504
192	0.0503	0.0503	0.0502	0.0502	0.0501	0.0500	0.0500	0.0499	0.0499	0.0498
193	0.0498	0.0497	0.0497	0.0496	0.0496	0.0495	0.0495	0.0494	0.0494	0.0493
194	0.0493	0.0492	0.0492	0.0491	0.0491	0.0490	0.0490	0.0489	0.0489	0.0488
195	0.0488	0.0487	0.0487	0.0486	0.0486	0.0485	0.0485	0.0484	0.0484	0.0483
196	0.0483	0.0482	0.0482	0.0481	0.0481	0.0480	0.0480	0.0479	0.0479	0.0478
197	0.0478	0.0477	0.0477	0.0476	0.0476	0.0475	0.0475	0.0474	0.0474	0.0474
198	0.0473	0.0473	0.0472	0.0472	0.0471	0.0471	0.0470	0.0470	0.0469	0.0469
199	0.0468	0.0468	0.0467	0.0467	0.0466	0.0466	0.0465	0.0465	0.0465	0.0464
200	0.0464	0.0463	0.0463	0.0462	0.0462	0.0461	0.0461	0.0460	0.0460	0.0459

TABLE 3 Repeatability of Machines

Hardness Range of Standardized Test Blocks	Repeatability of the Machine Should Be Less Than, %
For loads from 1 gf to <500 gf:	
Knoop:	
100 to 250, incl	6[A,B,C]
Over 250 to 650, incl	5[A,B]
Over 650	4[A,B]
Vickers:	
100 to 240, inc.	6[A,B,C]
Over 240 to 600, incl	5[A,B]
Over 600	4[A,B]
For loads from 500 gf to 1000 gf, incl:	
Knoop:	
100 to 250, incl	5[A,B,C]
Over 250 to 650, incl	4[A,B]
Over 650	3[A,B]
Vickers:	
100 to 240, incl	5[A,B,C]
Over 240 to 600, incl	4[A,B]
Over 600	3[A,B]

[A] $\bar{d} = (d_1 + d_2 + \ldots + d_5)/5$.

[B] In all cases the repeatability is the percentage given or 1 µm, whichever is greater.

[C] Due to the nature of materials currently available for test blocks in 100 HK to 250 HK and 100 HV to 240 HV ranges, percentage values noted represent repeatability of averages of 2 or more groups of 5 indentations each.

TABLE 4 Repeatability of Hardness Readings

Hardness Range for Standardized Test Blocks	Repeatability of the Test Block Readings Shall Be Less Than, %
For loads from 1 gf to <500 gf:	
Knoop:	
100 to 250, incl	5[A,B,C]
Over 250 to 650, inc.	4[A,B]
Over 650	3[A,B]
Vickers:	
100 to 240, incl	5[A,B,C]
Over 240 to 600, incl	4[A,B]
Over 600	3[A,B]
For loads from 500 gf to 1000 gf, incl:	
Knoop:	
100 to 250, incl	4[A,B,C]
Over 250 to 650, incl	3[A,B]
Over 650	2[A,B]
Vickers:	
100 to 240, incl	4[A,B,C]
Over 240 to 600, incl	3[A,B]
Over 600	2[A,B]

[A] $\bar{d}_1 = (d_1 + d_2 + \ldots + d_5)/5$.

[B] In all cases the repeatability is the percentage given or 1 µm, whichever is greater.

[C] Due to the nature of materials currently available for test blocks in 100 HK to 250 HK and 100 HV to 240 HV ranges, percentage values noted represent repeatability of averages of 2 or more groups of 5 indentations each.

ANNEX

(Mandatory Information)

A1. ADJUSTMENT OF ABBÉ-NELSON OR KOHLER ILLUMINATION SYSTEMS

A1.1 While some optical systems are permanently aligned, others have means of minor adjustments. To gain the utmost in resolution the operator should make the following adjustments:

A1.1.1 *Abbé-Nelson Illumination:*

A1.1.1.1 Focus to critical sharpness the surface of a flat polished specimen.

A1.1.1.2 Center the illuminating source.

A1.1.1.3 Centrally align the field and aperture diaphragms.

A1.1.1.4 Adjust the lamp so that the filament is in sharp focus in the specimen plane.

A1.1.1.5 Close the field diaphragm so that a thin, dark ring rims the field of view.

A1.1.1.6 Close the aperture diaphragm until the glare just disappears. Never close the diaphragm to the point where diffraction phenomena appear.

A1.1.1.7 Place a diffusing disk in back of the field diaphragm if the lamp is not a ribbon-filament type.

A1.1.1.8 If the light is too strong for eye comfort, reduce the intensity by the use of an appropriate neutral density filter or rheostat control.

A1.1.2 *Kohler Illumination:*

A1.1.2.1 Focus to critical sharpness the surface of a flat polished specimen.

A1.1.2.2 Center the illuminating source.

A1.1.2.3 Centrally align field and aperture diaphragms.

A1.1.2.4 Open the field diaphragm so that it just disappears from the field of view.

A1.1.2.5 Remove the eyepiece and examine the rear focal plane of the objective. If all the components are in their proper places, the source of illumination and the aperture diaphragm will appear in sharp focus.

A1.1.2.6 Full-aperture diaphragm is preferred for maximum resolving power. If glare is excessive, reduce the aperture; but never use less than the ¾ opening since resolution would be decreased and diffraction phenomena could lead to false measurements.

A1.1.2.7 If the light is too strong for eye comfort, reduce the intensity by the use of an appropriate neutral density filter or rheostat control.

APPENDIXES

(Nonmandatory Information)

X1. CORRELATION OF MICROHARDNESS TEST DATA BETWEEN LABORATORIES

X1.1 Scope

X1.1.1 This procedure provides guidance in establishing correlation of microhardness tests when two or more laboratories are involved.

X1.2 Significance

X1.2.1 Test Method E 384 establishes methods for determining microhardness of materials, verifying microhardness testing machines, and calibrating standardized test blocks. This appendix supports the method by guiding laboratories wishing to correlate their microhardness test data.

X1.3 Correlation Procedure

X1.3.1 All laboratories shall first establish that their test equipment conforms to the requirements in Test Method E 384.

X1.3.2 The specimens to be tested shall be taken from adjoining areas of the larger sample after all processing has been completed and prior to being sent to the cooperating laboratories for preparation and testing.

X1.3.3 The specimens shall be prepared for microhardness by the two or more laboratories using essentially the same procedures. If the specimens are capable of being prepared as metallographic specimens, established ASTM procedures shall be maintained uniformly among the laboratories as follows:

X1.3.3.1 The same surfaces shall be exposed for the microhardness test. This is to ensure that grain direction, if a characteristic, is taken into consideration.

X1.3.3.2 The surface preparation of the specimens shall be in accordance with Methods E 3.

X1.3.4 All laboratories shall calibrate the optics of their test apparatus with the same stage micrometer.

X1.3.5 The indentations shall be oriented the same relative to grain direction in order to avoid differences in results arising from this factor.

X1.3.6 The method of measuring the indentations shall be established prior to making the tests. It shall be the most accurate method as described by the equipment manufacturer.

X1.3.7 A minimum number of indentations shall be established. This shall conform to acceptable statistical methods of analysis, in accordance with Recommended Practice E 122.

X1.3.8 Each test specimen shall be indented and measured by the laboratory having prepared it, then sent with the

data for testing in the other laboratory or laboratories.

X1.3.8.1 After the specimens have been exchanged, each laboratory shall measure and record the indentations applied by the originating laboratory in a manner identical to the initial measurements.

X1.3.8.2 Each laboratory shall then repeat the indentation and measuring procedures as performed in X1.3.5 and X1.3.6, before sending the data and specimen to the remaining laboratory or laboratories.

X1.3.8.3 Each laboratory shall determine a set of microhardness values from the specimen they prepared, as well as sets of values they obtained by indenting and measuring specimens prepared by the other laboratory or laboratories.

X1.3.9 All data shall then be analyzed by the same acceptable statistical methods to establish the limits of agreement that are attainable between the two laboratories. As a minimum the following statistical data shall be evolved:

$\bar{X}$ = mean
σ = standard deviation
$\sigma/\bar{X}$ = standard error of the mean

X1.4 Referee

X1.4.1 If the laboratories cannot establish an acceptable correlation through this procedure, it will be necessary to introduce an independent laboratory to act as the referee.

X2. RESULTS OF INTERLABORATORY TEST OF THE MEASUREMENT OF MICROINDENTATIONS (5, 6)

X2.1 Introduction

X2.1.1 This interlaboratory test program was conducted to develop precision and bias estimates for the measurement of both Knoop and Vickers indentations using loads of 25 to 1000 gf for ferrous and nonferrous specimens covering a wide range of hardness.

X2.2 Scope

X2.2.1 This interlaboratory test program provides information on the measurement of the same indents by different laboratories in accordance with the procedures of Practice E 691.

X2.3 Referenced Documents

X2.3.1 *ASTM Standards:*

E 691 Conducting an Interlaboratory Test Program to Determine the Precision of Test Methods.[7]

X2.4 Procedure

X2.4.1 Five indents were made under controlled conditions at each losd (25, 50, 100, 200, 500, and 1000 gf), with both Knoop and Vickers indenters, using three ferrous and four nonferrous specimens.

X2.4.2 Twelve laboratories measured the indents on the ferrous specimens and twelve laboratories measured the indents on the nonferrous specimens (only two laboratories measured the indents on both the ferrous and nonferrous specimens).

X2.4.3 Each laboratory used the same stage micrometer to calibrate their measuring device.

X2.4.4 Results were tabulated and analyzed according to Practice E 691.

X2.5 Results

X2.5.1 For the three ferrous specimens, results from nine laboratories showed general agreement as to the diagonal sizes. Two other laboratories consistently undersized the indents (higher hardness) and one laboratory consistently oversized the indents (lower hardness). This bias was observed with both Vickers and Knoop indents sized by these laboratories with the degree of bias increasing as the indent size decreased and the specimen hardness increased. Test on the four nonferrous specimens produced general agreement but none of the three laboratories that produced biased results for the ferrous samples measured the nonferrous specimens.

X2.5.2 For the Vickers test data, the calculated hardness increased with increasing load and then became reasonably constant. This trend was apparent in the data from the nine consistent laboratories (ferrous specimens) and for the laboratory that oversized the indents. The two laboratories that undersized the indents became relatively constant. The load at which the hardness became relatively constant increased with increasing specimen hardness. For specimens below about 300 HV, there was relatively little difference in HV over the test load range.

X2.5.3 For the Knoop test data, all of the laboratories agreed that the hardness decreased continually with increasing test load and then became reasonably constant. The difference in HK values between low loads and high loads increased with increasing specimen hardness. For specimens with hardnesses below about 300 HK, the difference in hardness was quite small over the test load range.

X2.5.4 *Repeatability Interval*—The difference due to test error between two test results in the laboratory on the same material was calculated using the $(S_r)_j$ values, the pooled within-laboratory standard deviation. $(S_r)_j$ increased with diagonal size and the relationship varied for each material and test type. Table X2.1 lists regression equations that show the relationship between $(S_r)_j$ and the diagonal length in micrometers. The repeatability interval, $I(r)_j$, was calculated based on the relationships in Table X2.1. Because the repeatability intervals are also a function of diagonal length, regression equations were also calculated, Table X2.2. The repeatability intervals, in terms of Knoop and Vickers values for ferrous and nonferrous specimens, are shown in Figs. X2.1 to X2.4.

X2.5.5 *Reproducibility Interval*—The difference in test results on the same material in different laboratories was calculated using the $(S_R)_j$ values, the between-laboratory estimate of precision. $(S_R)_j$ increased with diagonal size and the relationship varied for each material and test type. Table X2.3 lists the regression equations that show the relationship

[7] *Annual Book of ASTM Standards*, Vol 14.02.

TABLE X2.1 Relationship Between Diagonal Length and $(S_r)_j$, the Pooled Within-Laboratory Standard Deviation

Material	Test	Regression Equation	Correlation Coefficient
Ferrous	Vickers	$(S_r)_j = 0.231 + 0.00284\bar{d}_1$	0.535
Ferrous	Knoop	$(S_r)_j = 0.216 + 0.006\bar{d}_1$	0.823
Nonferrous	Vickers	$(S_r)_j = 0.373 + 0.008\bar{d}_1$	0.862
Nonferrous	Knoop	$(S_r)_j = 0.057 + 0.0177\bar{d}_1$	0.8196

TABLE X2.2 Relationship Between the Diagonal Length and $I(r)_j$, the Repeatability Interval (±)

Material	Test	Regression Equation
Ferrous	Vickers	$I(r)_j = 0.653 + 0.008\bar{d}_1$
Ferrous	Knoop	$I(r)_j = 0.614 + 0.017\bar{d}_1$
Nonferrous	Vickers	$I(r)_j = 1.0556 + 0.0226\bar{d}_1$
Nonferrous	Knoop	$I(r)_j = 0.161 + 0.05\bar{d}_1$

TABLE X2.3 Relationship Between Diagonal Length and $(S_R)_j$, the Between-Laboratory Estimate of Precision

Material	Test	Regression Equation	Correlation Coefficient
Ferrous	Vickers	$(S_R)_j = 0.31 + 0.004\bar{d}_1$	0.747
Ferrous	Knoop	$(S_R)_j = 0.333 + 0.007\bar{d}_1$	0.899
Nonferrous	Vickers	$(S_R)_j = 0.357 + 0.0156\bar{d}_1$	0.8906
Nonferrous	Knoop	$(S_R)_j = 0.378 + 0.0177\bar{d}_1$	0.8616

TABLE. X2.4 Relationship Between the Diagonal Length and $I(R)_j$, the Reproducibility Interval (±)

Material	Test	Regression Equation
Ferrous	Vickers	$I(R)_j = 0.877 + 0.0113\bar{d}_1$
Ferrous	Knoop	$I(R)_j = 0.946 + 0.0198\bar{d}_1$
Nonferrous	Vickers	$I(R)_j = 1.0103 + 0.0441\bar{d}_1$
Nonferrous	Knoop	$I(R)_j = 1.07 + 0.05\bar{d}_1$

between $(S_R)_j$ and the diagonal length in micrometers. The reproducibility intervals, $I(R)_j$, was calculated based on the relationships shown in Table X2.3. Because the reproducibility intervals are also a function of diagonal length, regression equations were also calculated, Table X2.4. The reproducibility intervals, in terms of Knoop and Vickers values for the ferrous and nonferrous specimens, are shown in Figs. X2.1 to X2.4.

X2.5.6 The within-laboratory and between-laboratory precision values were calculated from $(V_r(\%))_j$ and $(V_L(\%))_j$ which are the coefficients of variation for within-laboratory and between-laboratory tests. Both are a function of the length of the length of the diagonal. The within-laboratory and between-laboratory precision values were relatively similar for both Vickers and Knoop test data, either ferrous or nonferrous. In general, the repeatability intervals and reproducibility intervals were larger than the precision estimates, particularly at low test loads and high sample hardnesses.

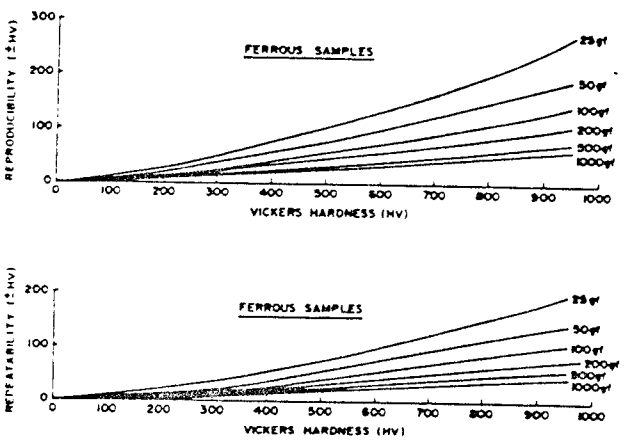


FIG. X2.1 Repeatability and Reproducibility Intervals in Terms of Vickers Hardness (±) for the Ferrous Samples as a Function of Test Load and Specimen Hardness

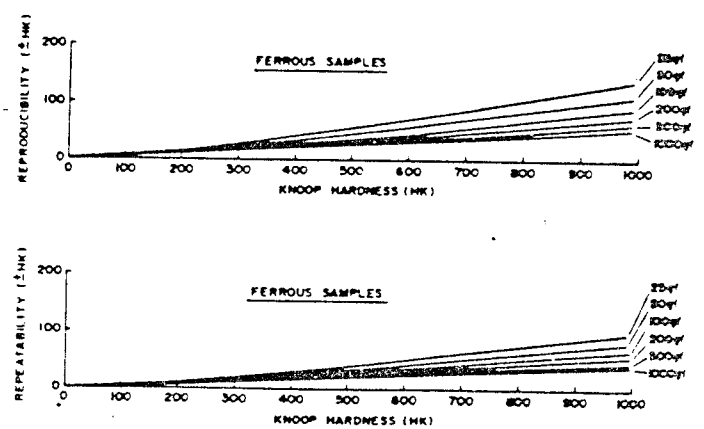


FIG. X2.2 Repeatability and Reproducibility Intervals in Terms of Knoop Hardness (±) for the Ferrous Samples as a Function of Test Load and Specimen Hardness

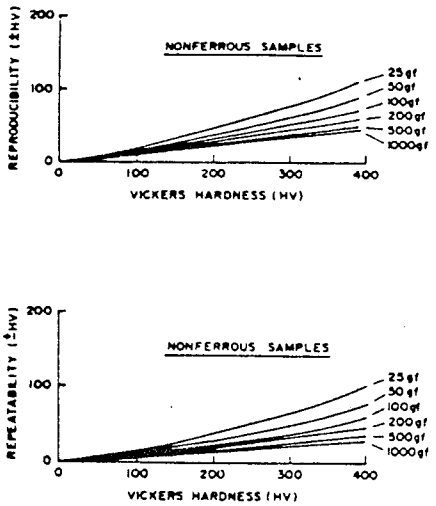


FIG. X2.3 Repeatability and Reproducibility Intervals in Terms of Vickers Hardness (±) for the Nonferrous Samples as a Function of Test Load and Specimen Hardness

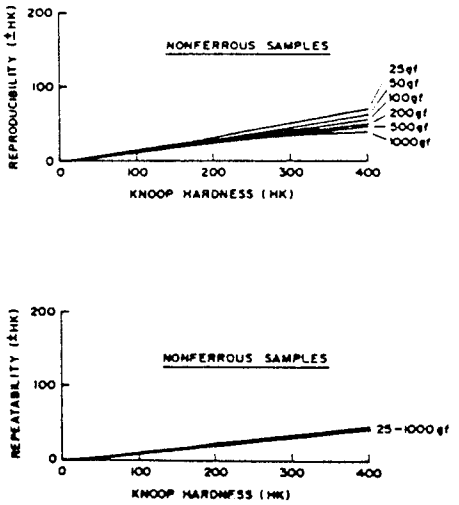


FIG. X2.4 Repeatability and Reproducibility Intervals in Terms of Knoop Hardness (±) for the Nonferrous Samples as a Function of Test Load and Specimen Hardness

REFERENCES

(1) Campbell, R. F., et al., "A New Design of Microhardness Tester and Some Factors Affecting the Diamond Pyramid Hardness Number at Light Loads," *Trans. ASM*, Vol 40, 1948, pp. 954–982.

(2) Kennedy, R. G., and Marrotte, N. W., "The Effect of Vibration on Microhardness Testing," *Materials Research and Standards*, Vol 9, November 1969, pp. 18–23.

(3) Brown, A. R. G., and Ineson, E., "Experimental Survey of Low-Load Hardness Testing Instruments," *J.I.S.I.*, Vol 169, 1951, pp. 376–388.

(4) Thibault, N. W., and Nyquist, H. L., "The Measured Knoop Hardness of Hard Substances and Factors Affecting Its Determination," *Trans. ASM*, Vol 38, 194, pp. 271–330.

(5) Tarasov, L. P., and Thibault, N. W., "Determination of Knoop Hardness Numbers Independent of Load," *Trans. ASM*, Vol 38, 194, pp. 331–353.

(6) Vander Voort, G. F., "Results of an ASTM E04 Round Robin on the Precision and Bias of Measurements of Microindentation Hardness.

APPENDIX H

ASTM METHOD E 534-86 FOR DETERMINATION OF PERCENT INSOLUBLE MATTER IN SODIUM CHLORIDE

Designation: E 534 – 86

Standard Test Methods for Chemical Analysis of Sodium Chloride[1]

This standard is issued under the fixed designation E 534; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 These test methods cover the chemical analyses usually required for sodium chloride.

1.2 The analytical procedures appear in the following sections:

	Section
Sample Preparation	5 to 9
Moisture	10 to 16
Water Insolubles	17 to 24
Calcium and Magnesium	25 to 31
Sulfate	32 to 38
Reporting of Analyses	39 to 41

1.3 The values stated in SI units are to be regarded as the standard.

1.4 *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 1193 Specification for Reagent Water[2]

E 180 Practice for Determining the Precision Data of ASTM Methods for Analysis and Testing of Industrial Chemicals[3]

E 200 Practice for Preparation, Standardization, and Storage of Standard Solutions for Chemical Analysis[3]

3. Significance and Use

3.1 Sodium chloride occurs in nature in almost unlimited quantities. It is a necessary article of diet as well as the source for production of many sodium compounds and chlorine. The methods listed in 1.2 provide procedures for analyzing sodium chloride to determine if it is suitable for its intended use.

4. Reagents

4.1 *Purity of Reagents*—Unless otherwise indicated, it is intended that all reagents should conform to the specifications of the Committee on Analytical Reagents of the American Chemical Society, where such specifications are available.[4]

4.2 *Purity of Water*—Unless otherwise indicated, references to water shall be understood to mean Type II or III reagent water conforming to Specification D 1193.

SAMPLE PREPARATION

5. Scope

5.1 This test method covers preparation of a sample that will be as representative as possible of the entire bulk quantity. The results of any analysis pertain only to the sample used.

6. Apparatus

6.1 *Coarse Grinder.*

6.2 *High-Speed Blender.*

6.3 *Oven.*

6.4 *Riffle Sampler.*

6.5 *Scale.*

7. Reagents

7.1 *Hydrochloric Acid, Standard* 1 *N* HCl—See Practice E 200.

8. Rock and Solar Salt Stock Solutions

8.1 Mix and split sample to 500 g, using the riffle sampler.

8.2 If sample appears wet, dry at 110°C for 2 h.

8.3 Grind the sample to −8 mesh in the coarse grinder.

8.4 Mix ground sample well and weigh out a 25.0-g representative portion for rock salt or 50.0 g for solar salt.

8.5 Place 200 mL of water in the high-speed blender and start at low speed.

8.6 Slowly add the salt sample to the high-speed blender and blend for 5 min.

8.7 Test for water insolubles as described in Sections 17 to 24.

8.8 Save filtrate from water insolubles test and dilute in a volumetric flask to 1 L with water as a stock solution for subsequent analyses.

9. Evaporated and Purified Salt Stock Solutions

9.1 Mix and split the sample to 100 g for evaporated salt, or 200 g for purified evaporated salt.

9.2 Transfer to a 1-L volumetric flask.

[1] These test methods are under the jurisdiction of ASTM Committee E-15 on Industrial Chemicals and are under the direct responsibility of Subcommittee E15.52 on Alkalies.

Current edition approved July 25, 1986. Published September 1986. Originally published as E 534 – 75. Last previous edition E 534 – 75 (1981).

[2] *Annual Book of ASTM Standards*, Vol 11.01.

[3] *Annual Book of ASTM Standards*, Vol 15.05.

[4] "Reagent Chemicals, American Chemical Society Specifications," American Chemical Society, Washington, DC. For suggestions on testing of reagents not listed by the American Chemical Society, see "Reagent Chemicals and Standards," by Joseph Rosin, D. Van Nostrand Co., Inc., New York, NY, and The "United States Pharmacopeia."

9.3 Add 800 mL of water and allow the salt to dissolve.

9.4 Add 2 mL of concentrated HCl to dissolve any water insoluble calcium salts, particularly calcium carbonate.

9.5 Dilute to volume with water and use as a stock solution for subsequent analyses.

MOISTURE

10. Scope

10.1 This test method determines free moisture in the salt over a concentration range from 0.00 to 0.04 %. It does not determine occluded moisture trapped within the salt crystals. The procedure is based on weight loss after a sample is heated to volatize moisture.

11. Apparatus

11.1 *Analytical Balance.*

11.2 *Desiccator.*

11.3 *Oven.*

12. Procedure, Rock and Solar Salt

12.1 Weigh 100 g of salt to the nearest 0.05 g into a previously dried and tared moisture dish.

12.2 Dry at 110°C for 2 h.

12.3 Cool in a desiccator and weigh.

13. Procedure, Evaporated and Purified Evaporated Salt

13.1 Weigh 20 g of salt to the nearest 0.001 g into a previously dried and weighed glass weighing bottle and cover.

13.2 Dry at 110°C for 2 h.

13.3 Cool in a desiccator, replace cover, and weigh.

14. Calculation

14.1 Calculate the percentage of moisture as follows:

$$\text{Moisture, \%} = \frac{A}{B} \times 100$$

where:

A = loss of weight on drying, g, and

B = weight of sample, g.

15. Report

15.1 Report the moisture content to the nearest decimal percentage shown in Table 1. Duplicate determinations that agree within the percent absolute as specified in Table 1 are acceptable for averaging (95 % confidence level).

16. Precision and Bias

16.1 The following criteria should be used in judging the acceptability of results:

16.1.1 *Repeatability (Single Analyst)*—The standard deviation of results (each the average of duplicates), obtained by the same analyst on different days, has been estimated at the values shown in Table 2. Two such averages should be considered suspect (95 % confidence level) if they differ by more than the values in this table (Note 1).

TABLE 1 Percentage of Moisture

Range, %	Report to, %	Checking Limits
0.003 to 0.004	0.001	0.004
0.025 to 0.035	0.001	0.020

16.1.2 *Reproducibility (Multilaboratory)*—The standard deviation of results (each the average of duplicates), obtained by analysts in different laboratories has been estimated at the values given in Table 2. Two such averages should be considered suspect (95 % confidence level) if they differ by more than the values in this table (Note 1).

NOTE 1—The above precision estimates are based on an interlaboratory study[5] with five samples of sodium chloride covering the above ranges of moisture. One analyst in each of ten laboratories performed duplicate determinations and repeated 1 day later.

16.2 The bias of this test method has not been determined.

WATER INSOLUBLES

17. Scope

17.1 This gravimetric method determines only the amount of insolubles present in sodium chloride which will not dissolve in water.

18. Apparatus

18.1 *Analytical Balance.*

18.2 *Desiccator.*

18.3 *Magnetic Stirrer with Stirring Bar.*

18.4 *Parabella Filter Funnel Assembly,*[6] 1000-mL, or its equivalent with 0.3-μm glass fiber filter disk.

19. Reagents

19.1 *Silver Nitrate, Standard Solution,* 0.1 *N* $AgNO_3$—See Practice E 200.

20. Procedure, Rock and Solar Salts

20.1 Transfer a sample prepared in accordance with 8.1 to 8.6 to a 1-L Erlenmeyer flask, washing out the blender with 100 mL of water. Add 300 mL of water to give a total of 600 mL of water added.

20.2 Stir on a magnetic stirrer for 1 h. Adjust the stirrer speed to give maximum agitation without danger of losing any sample due to splashing. Place a beaker over top of the flask while stirring.

20.3 Filter the solution by vacuum through a previously dried (110°C for 1 h) and accurately weighed filter disk using the Parabella funnel. Transfer all insolubles to the paper and wash free of chlorides with water until the filtrate shows no turbidity when tested with 0.1 *N* $AgNO_3$ solution.

20.4. Dilute filtrate and washings to 1 L with water in volumetric flask.

20.5 Dry the filter disk at 110°C for 1 h.

20.6 Cool in a desiccator and weigh the disk on an analytical balance.

20.7 Save the filtrate for subsequent analyses.

[5] Supporting data are available at ASTM Headquarters. Request RR: E-15-1023.

[6] Fisher Scientific No. 9-730-200 has been found satisfactory.

TABLE 2 Precision Estimates (Moisture)

Range, %	Repeatability			Reproducibility		
	Standard Deviation	Degrees of Freedom	95 % Confidence Level	Standard Deviation	Degrees of Freedom	95 % Confidence Level
0.003 to 0.004	0.00223	18	0.007	0.00322	8	0.010
0.025 to 0.035	0.00428	30	0.01	0.0138	9	0.04

21. Procedure, Evaporated and Purified Evaporated Salts

21.1 Place a well mixed sample in a 2-L beaker. Use 100-g sample for evaporated or 200 g for purified evaporated salt.

21.2 Add 750 mL of water.

21.3 Mix with a mechanical stirrer until solution is complete.

21.4 Filter the solution by vacuum through a previously dried (110°C for 1 h) and accurately weighed filter disk using the Parabella funnel. Transfer all insolubles to the paper and wash free of chlorides with water until the filtrate shows no turbidity when tested with 0.1 N $AgNO_3$ solution.

21.5 Dry the filter disk at 110°C for 1 h.

21.6 Cool in a desiccator and weigh on an analytical balance.

21.7 Dilute the filtration and washings to 1 L with water in a volumetric flask and reserve for subsequent analyses.

22. Calculation

22.1 Calculate the percentage of water insolubles as follows:

$$\text{Insolubles, \%} = \frac{A}{B} \times 100$$

where:

A = increase in weight of filter disk, g, and
B = sample weight, g.

23. Report

23.1 Report the percentage of water insolubles in the nearest decimal percentage shown in Table 3. Duplicate determinations that agree within the percent relative as specified in Table 3 are acceptable for averaging (95 % confidence level).

24. Precision and Bias

24.1 The following criteria should be used in judging the acceptability of results:

24.1.1 *Repeatability (Single Analyst)*—The coefficient of variation of results (each the average of duplicate determinations), obtained by the same analyst on different days, was estimated to be 23.5 % relative at 57 degrees of freedom. Two such averages should be considered suspect (95 % confidence level) if they differ by more than 70 % relative (Note 2).

24.1.2 *Reproducibility (Multilaboratory)*—The coefficient of variation of results (each the average of duplicate determinations), obtained by analysts in different laboratories has been estimated at the values given in the table below. Two such averages should be considered suspect (95 % confidence level) if they differ by more than the values in Table 4 (Note 2).

NOTE 2—The above precision estimates are based on an interlaboratory study[5] with six samples of sodium chloride covering the above ranges of water insolubles. One analyst in each of ten laboratories performed duplicate determinations and repeated 1 day later. Practice E 180 was used in developing these precision estimates.

24.2 The bias of this test method has not been determined.

TABLE 3 Percentage of Water Insolubles

Range, %	Report to, %	Checking Limits
0.002 to 0.005	0.001	65
0.01 to 0.04	0.01	65
0.15 to 0.35	0.01	65

CALCIUM MAGNESIUM

25. Scope

25.1 This test method covers the EDTA titrimetric determination of calcium and magnesium and the EDTA titrimetric determination of calcium. The magnesium content is determined by difference.

26. Apparatus

26.1 *Magnetic Stirrer with Stirring Bar.*

27. Reagents

27.1 *Eriochrome Black T Indicator Solution, Hydroxy Naphthol Blue*, or its equivalent.

27.2 *Murexide (Ammonium Purpurate)* Indicator Solution, or its equivalent.

27.3 *EDTA Standard Solution* (1 mL = 0.400 mg calcium)—Dissolve 4.0 g of disodium dihydrogen ethylene diaminetetraacetate (EDTA) in 1 L of water. Standardize this solution against a standard calcium solution prepared by dissolving 1.000 g of $CaCO_3$ and 2 mL of HCl in water and diluting to 1 L with water in a volumetric flask. Obtain an exact factor for the EDTA solution. This factor is equal to the milligrams of calcium equivalent to 1.00 mL of EDTA solution. See Practice E 200.

TABLE 4 Precision Estimates (Water Insolubles)

Range, %	Coefficient of Variation	Degrees of Freedom	Range, 95 % Confidence Level
0.002 to 0.005	91.7	9	300, relative
0.01 to 0.04	42.2	8	140, relative
0.15 to 0.35	20.5	9	65, relative

$$\text{Factor} = \frac{W'}{V'}$$

where:

W' = calcium in aliquot, mg, and
V' = EDTA solution required for titration, mL.

27.4 *Ammonium Chloride–Ammonium Hydroxide Solution*—Add 67.5 g of ammonium chloride (NH_4Cl) to 570 mL of ammonium hydroxide (NH_4OH) contained in a 1-L volumetric flask. Reserve this solution for use as described in 27.6 and 27.7.

27.5 *Potassium Cyanide Solution* (50 g/L)—Dissolve 50 g of potassium cyanide (KCN) in water and dilute to 1 L with water. Store in a borosilicate glass bottle. **Caution:** Potassium cyanide is extremely poisonous.

27.6 *Magnesium Sulfate Solution* (2.5 g/L)—Dissolve 2.5 g of $MgSO_4 \cdot 7H_2O$ in water and dilute to volume with water in a 1-L volumetric flask. Determine the volume of EDTA solution equivalent to 50 mL of $MgSO_4$ solution as follows: Pipet 50.0 mL of $MgSO_4$ solution into a 400-mL beaker. Add 200 mL of water and 2 mL of NH_4Cl:NH_4OH solution (27.4). Add 1 mL of KCN solution and a sufficient amount of Eriochrome Black T Indicator solution or its equivalent. Titrate the solution with EDTA solution while stirring with a magnetic stirrer to the true blue end point. This gives the volume of EDTA solution equivalent to 50.0 mL of $MgSO_4$ solution.

27.7 *Buffer Solution*—Pipet 50 mL of $MgSO_4$ solution into the volumetric flask containing the remaining $NH_4Cl \cdot NH_4OH$ solution (27.4). Add the exact volume of EDTA solution equivalent to 50 mL of the $MgSO_4$ solution. Dilute to 1 L with water. Store the solution in a polyethylene bottle.

27.8 *Potassium Hydroxide Solution* (600 g/L)—Dissolve 150 g of potassium hydroxide (KOH) in 250 mL of water. Cool and store in a polyethylene bottle.

28. Procedure

28.1 Using Table 5 as a guide, pipet two aliquots of stock solution into 400-mL beakers to give a titer between 2 and 10 mL of standard EDTA solution. One aliquot is used to determine calcium and the other for total calcium and magnesium.

28.2 Dilute to 200 mL with water, if necessary, and place on magnetic stirrer.

28.3 *Total Calcium and Magnesium*:

28.3.1 Add 5 mL of buffer solution, 1 mL of KCN solution, and a sufficient amount of Eriochrome Black T Indicator Solution or its equivalent.

28.3.2 Titrate with standard EDTA solution to a true blue color.

28.3.3 Record the millilitres used as Titration 1 (T_1).

TABLE 5 Stock Solutions (Calcium and Magnesium)

Stock Solution	Aliquot, mL
Kansas rock salt	10
Northern rock salt	25
Southern rock salt	50
Evaporated salt	50
Purified salt	200
Solar salt	100

28.4 *Calcium Only*:

28.4.1 Add 2 mL of KOH solution, 1 mL of KCN solution and stir for about 2 min to precipitate magnesium.

28.4.2 Add a sufficient amount of murexide solution or an equivalent calcium indicator solution.

28.4.3 Titrate with standard EDTA solution to a true blue color.

28.4.4 Record the millilitres used as Titration 2 (T_2).

29. Calculation

29.1 Calculate the weight percent of calcium as follows:

$$\text{Ca, weight \%} = \frac{(T_2)\,(\text{factor})\,(0.1)}{S}$$

where:

T_2 = EDTA used to titrate calcium only, mL.
S = weight of salt in aliquot, g.

29.1.1 See 27.3 for factor.

29.2 Calculate the weight percent of magnesium as follows:

$$\text{Mg, weight \%} = \frac{(T_1 - T_2)\,(\text{factor})\,(0.6064)\,(0.1)}{S}$$

where:

T_1 = EDTA used to titrate total calcium and magnesium, mL, and
S = weight of salt in aliquot, g.

30. Report

30.1 Report the percentage of calcium to the nearest 0.001 %. Duplicate determinations that agree within 10 % relative are acceptable for averaging (95 % confidence level) (see Note 3).

30.2 Report the percentage of magnesium to the nearest percent given in Table 6. Duplicate determinations which agree within the percent absolute as specified in Table 6 are acceptable for averaging (95 % confidence level) (see Note 4).

31. Precision and Bias

31.1 The following criteria should be used in judging the acceptability of calcium results:

31.1.1 *Repeatability (Single Analyst)*—The coefficient of variation of results (each the average of duplicate determinations) obtained by the same analyst on different days, was estimated to be 6.34 % relative at 48 degrees of freedom. Two such averages should be considered suspect (95 % confidence level) if they differ by more than 18 % relative.

31.1.2 *Reproducibility (Multilaboratory)*—The coefficient of variation of results (each the average of duplicate determinations), obtained by analysts in different laboratories has been estimated to be 9.82 % relative at 9 degrees of freedom. Two such averages should be considered suspect

TABLE 6 Percentage of Magnesium

Range, %	Report to, %	Check Limits
0.001 to 0.003	0.001	0.002
0.020 to 0.025	0.001	0.010

(95 % confidence level) if they differ by more than 30 % relative.

NOTE 3—The above precision statements are based on an interlaboratory study[5] with five samples of sodium chloride covering the range from 0.036 to 0.909 % calcium. One analyst in each of eight laboratories performed duplicate determinations and repeated 1 day later. Practice E 180 was used in developing these precision estimates.

31.1.3 The bias of this test method has not been determined.

31.2 The following criteria should be used in judging the acceptability of magnesium results:

31.2.1 *Repeatability (Single Analyst)*—The standard deviation results (each the average of duplicates), obtained by the same analyst on different days, has been estimated at the values shown in Table 7. Two such averages should be considered suspect (95 % confidence level) if they differ by more than the values in Table 7 (Note 4).

31.2.2 *Reproducibility (Multilaboratory)*—The standard deviation of results (each the average of duplicate determinations), obtained by analysts in different laboratories has been estimated at the values given in Table 7. Two such averages should be considered suspect (95 % confidence level) if they differ by more than the values in Table 7 (Note 4).

NOTE 4—The above precision statements are based on an interlaboratory study[5] of six samples of sodium chloride covering the above ranges of magnesium. One analyst in each of ten laboratories performed duplicate determinations and repeated 1 day later. Practice E 180 was used in developing these precision estimates.

31.2.3 The bias of this test method has not been determined.

SULFATE

32. Scope

32.1 This test method covers the gravimetric determination of the sulfate content of sodium chloride.

33. Apparatus

33.1 *Gooch Asbestos Slurry.*
33.2 *Gooch Filtering Crucible and Holder.*
33.3 *Muffle Furnace.*
33.4 *Oven.*

34. Reagents

34.1 *Barium Chloride, Standard Solution* 10 % $BaCl_2$—See Practice E 200.

34.2 *Hydrochloric Acid Standard Solution* 1 *N* HCl—See Practice E 200.

34.3 *Methyl Orange Indicator solution*—See Practice E 200.

35. Procedure

35.1 Using Table 8 as a guide, pipet the recommended aliquot of stock solution into a 400-mL beaker.

35.2 Dilute to 200 mL, add a few drops of methyl orange indicator solution and acidify with 1 mL of HCl (1+1) if necessary.

35.3 Heat solution gently to boiling and add 10 mL of $BaCl_2$ solsution dropwise while stirring.

35.4 Digest on a hot plate below the boiling point for 30 min.

35.5 Cool overnight.

35.6 Filter through a tared Gooch crucible previously prepared with an asbestos mat and ignited in a muffle furnace at 800°C for 30 min. Transfer all the precipitate to the crucible with a rubber policeman. Wash with portions of hot water until washings are free of chlorides.

35.7 Dry the crucible at 110°C for 15 min, then ignite in a muffle furnace at 800°C for 30 min.

35.8 Cool in a desiccator and reweigh.

36. Calculation

36.1 Calculate percentage of sulfate as follows:

$$\text{Sulfate, \%} = \frac{A}{B} \times 0.4115 \times 100$$

where:

A = weight of precipitate, g, and
B = weight of salt in aliquot, g.

37. Report

37.1 Report the percentage of sulfate to the nearest 0.001 %. Duplicate determinations that agree within 20 % relative are acceptable for averaging (95 % confidence level) (see Note 5).

38. Precision and Bias

38.1 The following criteria should be used in judging the acceptability of sulfate results:

38.1.1 *Repeatability (Single Analyst)*—The coefficient of variation of results (each the average of duplicate determinations) obtained by the same analyst on different days was estimated to be 8.03 % relative at 60 degrees of freedom. Two such averages should be considered suspect (95 % confidence level) if they differ by more than 23 % relative.

38.1.2 *Reproducibility (Multilaboratory)*—The coefficient of variation of results (each the average of duplicate determinations) obtained by the same analyst on different days, was estimated to be 8.01 % relative at 9 degrees of freedom. Two such averages should be considered suspect (95 % confidence level) if they differ by more than 26 % relative.

NOTE 5—The above precision estimates are based on an interlaboratory study[5] of six samples of sodium chloride covering the range from 0.016 to 2.030 % sulfate. One analyst in each of ten laboratories performed duplicate determinations and repeated 1 day later. Practice E 180 was used in developing these precision estimates.

38.1.3 The bias of this test method has not been determined.

REPORTING OF ANALYSES

39. Scope

39.1 Analyses should be reported on a dry basis. If analyses are on an as received sample, correction should be made by converting to a dry basis. Sodium chloride purity is determined by subtracting the total percentage of impurities from 100. Moisture should be reported as a separate value.

TABLE 7 Precision Estimates (Calcium and Magnesium)

Range, %	Repeatability			Reproducibility		
	Standard Deviation	Degrees of Freedom	Range, 95 % Confidence Level	Standard Deviation	Degrees of Freedom	Range, 95 % Confidence Level
0.001 to 0.003	0.00066	28	0.002	0.00147	8	0.005
0.02 to 0.025	0.033	26	0.096	0.0042	8	0.014

TABLE 8 Stock Solutions (Sulfate)

Stock Solution	Aliquot, mL
Rock salt	40
Evaporated salt	100
Purified evaporated salt	200
Solar salt	100

40. Procedure

40.1 Convert sulfate to calcium sulfate and the unused calcium to calcium chloride unless the sulfate in sample exceeds the quantity necessary to combine with the calcium. In this case, convert the calcium to calcium sulfate and the unused sulfate first to magnesium sulfate, and the remaining sulfate, if any, to sodium sulfate. Convert the unused magnesium to magnesium chloride.

40.2 Report rock and solar salt impurities to the second decimal place and salt purity, by difference, to the first decimal place.

40.3 Report evaporated salt impurities to the third decimal place and salt purity, by difference, to the second decimal place.

40.4 Report purified salt impurities to the fourth decimal place and salt purity, by difference, to the third decimal place.

41. Conversion Factors

$BaSO_4 \times 0.4116 = SO_4$
$BaSO_4 \times 0.5832 = CaSO_4$
$BaSO_4 \times 0.6086 = Na_2SO_4$
$Ca \times 3.3967 = CaSO_4$
$Ca \times 0.6064 = Mg$
$CaSO_4 \times 0.2944 = Ca$
$CaSO_4 \times 0.8153 = CaCl_2$
$CaSO_4 \times 0.8842 = MgSO_4$
$CaSO_4 \times 1.0434 = Na_2SO_4$
$Mg \times 3.9173 = MgCl_2$
$MgCl_2 \times 1.4296 = CaSO_4$
$MgCl_2 \times 1.2641 = MgSO_4$
$MgSO_4 \times 1.4299 = CaSO_4$
$MgSO_4 \times 1.1311 = MgCl_2$
$MgSO_4 \times 1.1800 = Na_2SO_4$
$SO_4 \times 1.4173 = CaSO_4$

The American Society for Testing and Materials takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, 1916 Race St., Philadelphia, PA 19103.

APPENDIX I

COST CONSIDERATIONS FOR ANTISKID MATERIALS

COST CONSIDERATIONS FOR ANTISKID MATERIALS[1]

I.1 PURCHASE COSTS

The cost of a deicing material is dependent on availability, abundance, and amount needed. The most readily available and widely used are rock salt and abrasives treated as necessary with calcium chloride. A comparison of cost relating these to other materials can be seen in Table I-1.

Due to increased costs, alternative methods to salt and abrasives are often avoided. Calcium magnesium acetate (CMA) is a favorable alternative to salt with regard to its noncorrosive effects and high solubility, yet the purchase price is approximately 34 times that of salt. This would suggest the limited use of the product for areas such as bridge decks where corrosion is a severe problem. Other chemicals that are inhibited by cost are aluminum chloride and lithium chloride costing 20 and 333 times that of salt, respectively.

I.2. APPLICATION AND CLEANUP COSTS

Purchase price is not the only consideration when implementing an ice and snow control program. The application of salts has been estimated at $200 million a year (Iowa Department of Transportation Planning and Research Division, 1980). This includes the purchase of equipment and labor costs. Abrasives also require spring cleaning, estimated at an annual $4 million (Anonymous, 1988). A favorable alternative method would be one that was inexpensive to implement, yet required no cleanup.

Many of the alternative methods under consideration require large initial investments and continued maintenance, thus not competing with the present salt/abrasive system. Tables I-2 and I-3 show relative costs of some alternative deicing chemicals and snow/ice removal methods, respectively. Embedded pipes, for example, cost approximately $4.00 per square foot for a completely self-contained system. Annual operational costs vary due to the heat source used. If purchased steam power is used, one could expect a cost in excess of $0.133 per square foot (Jorgensen, 1964). Escalated costs would also result from repairs that require stripping of pavement.

I.3 CORROSION COSTS

Damage due to chemicals has been observed in automobiles, bridges, and in the roadside environment. Corrosion to automobiles has been a widely researched topic, yet, it is still hard to pinpoint in exact dollar figures the amount of damage (much of which is vehicle depreciation). The following quotation describes the corrosion process, "After a road salt spray, the automobile owner will observe a white salt film during the low

[1] References listed in Section 8 of main report.

TABLE I-1. COST DATA FOR DEICING CHEMICALS

Material	Relative cost[a]	Representative cost ($/ton)	Reference
Sodium chloride	1X	25-34.79	Wood (1983); phone survey
Potassium chloride	4X	30.00	Wood (1983); Welch (1976)
Ammonium sulfate	4X	31.00	Wood (1983); Welch (1976)
Calcium chloride	8X	98.04	Wood (1983); phone survey
Methanol	8X		Wood (1983)
Urea	11X	9.00	Wood (1983); Welch (1976)
Urea:Ca formate (2:1)	14X		Wood (1983)
Magnesium chloride	14X	67.00	Wood (1983); Anonymous (1988)
Fertilizer	19X		Wood (1983)
Aluminum chloride	20X	320.00	Wood (1983); Welch (1976)
Ethylene glycol	27X	0.72/gal	Wood (1983); Transportation Research Board (1984)
Urea:calcium formate:formamide (1:1:1)	27X		Wood (1983)
Calcium magnesium acetate (CMA)	34X	600.00	Wood (1983); McElroy (1988)
Tetrapotassium pyrophosphate	41X		Wood (1983)
Propylene glycol	50X		Wood (1983)
Lithium chloride	333X	1740.00	Wood (1983); Welch (1976)
Sand	—	2-4.25	Phone survey
Aggregate	—	6.10	Welch (1976)
Aggregate lime	—	4.76	Welch (1976)

[a] Compared to sodium chloride (rock salt).

TABLE I-2. RELATIVE CAPITAL COST OF ALTERNATIVE DEICING CHEMICALS

Chemical	Relative cost ($/lb)[a]
Methanol	0.7X
Ethanol	2X
Isopropanol	1.6X
Acetone	1.9X
Urea	1X
Formamide	4.4X
Dimethyl sulfoxide	5.9X
Ethyl carbonate (urethane)	4X
Verglimit-modified asphalt	0.5X

[a] Cost relative to urea (1979 dollars).

TABLE I-3. RELATIVE CAPITAL COST OF ALTERNATIVE SNOW/ICE REMOVAL METHODS

Method	Relative cost ($/ft^2)[a]
Modified traffic paint	0.04X
Waterproofing compound (with silicone rubber)	0.06X
UCAR	0.12X
Infrared generator	3.1X
Embedded pipes	1X
Embedded electrical elements	1.4X
Conductive asphalt	0.4X[b]

[a] Cost relative to embedded pipes.

[b] Cost will also include the purchase of a protective coating.

humidity hours, as the humidity increases it disappears, forming a corrosive liquid" (Baboian, 1988). This process continues from day to night, and is accelerated with warmer temperatures. It has been estimated that $200 to $300 in damage is done per vehicle each year due to road salt (EPA, 1972).

Damage to bridge decks results from: scaling (due to chloride concentrations that causes the freezing point of layers to be different and thus freeze at different times); reinforcing steel corrosion (from chlorine ion concentration); dealimentation (cracks resulting from pressure since the volume of iron oxide is larger than that of the original steel); and spalling (occurring over reinforcing steel with portions of concrete removed) of pavement (Welch, 1976). Another corrosive effect can be seen in the deterioration of road markings such as paints, plastic, and tape (Slick, 1988). As an example, Brown (1988) estimated an average repair cost of $40 per square yard (not including traffic control) for bridge decks.

Other than fugitive dust, it is difficult to assess the cost of environmental damage due to deicing chemicals. Damage can be observed in roadside vegetation and water. Damage to trees and vegetation has been estimated at $50 million a year (Wood, 1983). Water pollution costs weigh most heavily in the contamination of wells that require replacing and also medical bills, not to mention court costs. Table I-4 illustrates approximate costs of corrosion and environmental damages due to deicing salts.

I.4 GENERAL COST CONSIDERATIONS

As can be observed by comparing Tables I-2 and I-3, the capital cost of alternative ice and snow control methods place their possibility for use in the distant future. Favorable aspects, such as noncorrosive and nonpolluting characteristics, have not as yet outweighed the need for an economically feasible method of snow and ice control. However, the unfavorable affects of salt and abrasives will promote the continued search for more favorable cost-effective alternatives.

For now, it can be surmised that the most cost-effective ice/snow control method is the continued use of rock salt and abrasives. It is advisable that calcium chloride be used only when conditions warrant. The use of a substitute chemical (e.g., CMA) may be necessary on limited areas such as bridge decks to inhibit the corrosive effects that result from the use of salts and chlorides.

TABLE I-4. RECENT ESTIMATES OF CORROSION AND ENVIRONMENTAL COSTS DUE TO CHEMICAL USE[a]

Auto corrosion ($\$10^6$/yr)	Infrastructure damage ($\$10^6$/yr)	Environmental damage ($\$10^6$/yr)
2,000	500	210
643	160	12[d]
70,000[b]	200[c]	

[a] 1976-1981 dollars.

[b] McDonald, 1981.

[c] Murray & Ernst, 1976.

[d] Iowa DOT, 1980.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA - 450/3-90-007	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Guidance Document for Selecting Antiskid Materials Applied to Ice- and Snow-Covered Roadways		5. REPORT DATE July 1991
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Emission Standards Division (MD-13) Office Of Air Quality Planning and Standards U.S. Environmental Protection Agency Research Triangle Park, North Carolina 27711		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO. 68-D0-0123 Work Assignment No. 6
12. SPONSORING AGENCY NAME AND ADDRESS U.S. Environmental Protection Agency Office of Air Quality Planning and Standards Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final
		14. SPONSORING AGENCY CODE EPA/200/04

15. SUPPLEMENTARY NOTES

16. ABSTRACT

This report describes a study whose primary purpose was to provide guidance on methods to determine: (1) the physical properties and durability of antiskid material selected for use on ice and snow-covered roadways; and (2) criteria for defining the elements of an effective PM_{10} emission control strategy associated with the use of antiskid materials. This report is expected to be used by local, State, and regional air pollution control agencies to identify antiskid materials that are both durable and effective and produce fewer PM_{10} emissions.

Phase 1 of the study collected background information to derive preliminary selection criteria for antiskid materials based on existing data. Phase 2 was a laboratory evaluation to: (a) determine the physical properties of typical antiskid materials and (b) conduct suitable tests of antiskid materials to determine their potential for the generation of PM_{10} emissions. Based on limited data, the class of materials that is relatively hard as indicated by low silt content, low abrasion loss and high values for the Vickers hardness test, had the lowest overall potential for silt generation. The best overall indicator of silt generation potential appeared to be the Los Angeles abrasion loss.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air pollution Fugitive emissions PM_{10} emissions Antiskid materials Deicing chemicals Paved roads		

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES
	20. SECURITY CLASS (This page) Unclassified	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE