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

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GUIDANCE DOCUMENT FOR SELECTING ANTISKID MATERIALS APPLIED TO ICE- AND SNOW-COVERED ROADWAYS

FINAL REPORT

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PREFACE

This report was prepared for the Office of Air Quality Planning and Standards (OAQPS), U.S. Environmental Protection Agency (EPA), under EPA Contract No. 68-02-4395, Assignment No. 31. Mr. Larry Elmore was the requestor of this work. The report was prepared by Mr. John S. Kinsey, Dr. Chatten Cowherd, and Ms. Karen Connery of Midwest Research Institute.

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EXECUTIVE SUMMARY

PM_{10} emissions generated by traffic resuspension of dry paved surface materials vary directly with the road surface silt loading (particles < 75 μm physical diameter). The application of antiskid materials to snow- and ice-covered roadways causes a substantial increase in silt loading and thus PM_{10} emissions.

This document provides air pollution control agencies with information on physical properties of antiskid materials that determine their potential for increasing road surface silt loading, particularly the initial silt content and durability of abrasive materials. Durability is defined as the resistance of an antiskid abrasive to generate silt sized particles. The Los Angeles abrasion test is recommended as an appropriate measurement of overall aggregate durability. A dry sieving procedure is described to measure silt content.

The effectiveness of an abrasive material to increase vehicle skid resistance on snow or ice is a function of particle size, shape, hardness, and durability. Durability is also shown to be related to particle size, shape, and hardness. A high quartz (> 90%), coarse grained (> 16 mesh), hard (Vickers hardness > 1,000 kg/mm²) material with low silt content (< 1% and a high degree of angularity (> 50% void fraction) is appropriate for antiskid application and is expected to contribute the least to PM_{10} emissions. A good quality, washed construction aggregate (e.g., sand) is often the best choice.

There is a significant potential for PM_{10} emissions from rock salt, but basic information is lacking on the dried materials (NaCl and impurities) that are available for resuspension by traffic. Most of the soluble salt is believed to wash off the roadway with the melting snow and ice. Only salts that have a small amount (< 2%) of insoluble matter should be used because that portion is likely to consist of very small particles in the silt sized fraction.

This study also presents a review of current sanding and salting practices based on information from selected state and municipal transportation agencies. It was determined that excessive silt loading (and thus PM_{10} emissions) are likely because of overapplication of antiskid materials and from noncompliance with recommended silt and durability specifications.

Finally, information is supplied on how to utilize material physical properties to select an antiskid material that potentially will produce less PM_{10} emissions, and yet assure safe streets and highways during winter months. A decision "tree" has been developed for material selection. The first step is to define the road, traffic, and icing conditions. From that point, candidate materials can be chosen based on silt generation potential, cost, and availability.

SECTION 1

INTRODUCTION

Several areas of the country which are in violation of the National Ambient Air Quality Standard for PM_{10} (airborne particles of diameter less than or equal to 10 μmA) 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 similar materials applied to the road surface to improve traction on snow- and ice-covered roadways. Deicers 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 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):

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

where: e = PM_{10} emission factor (g/VKT)
L = total road surface dust loading (g/m²)
s = surface silt content, fraction of particles < 75 μm diameter (American Association of State Highway and Transportation Officials, 1984)

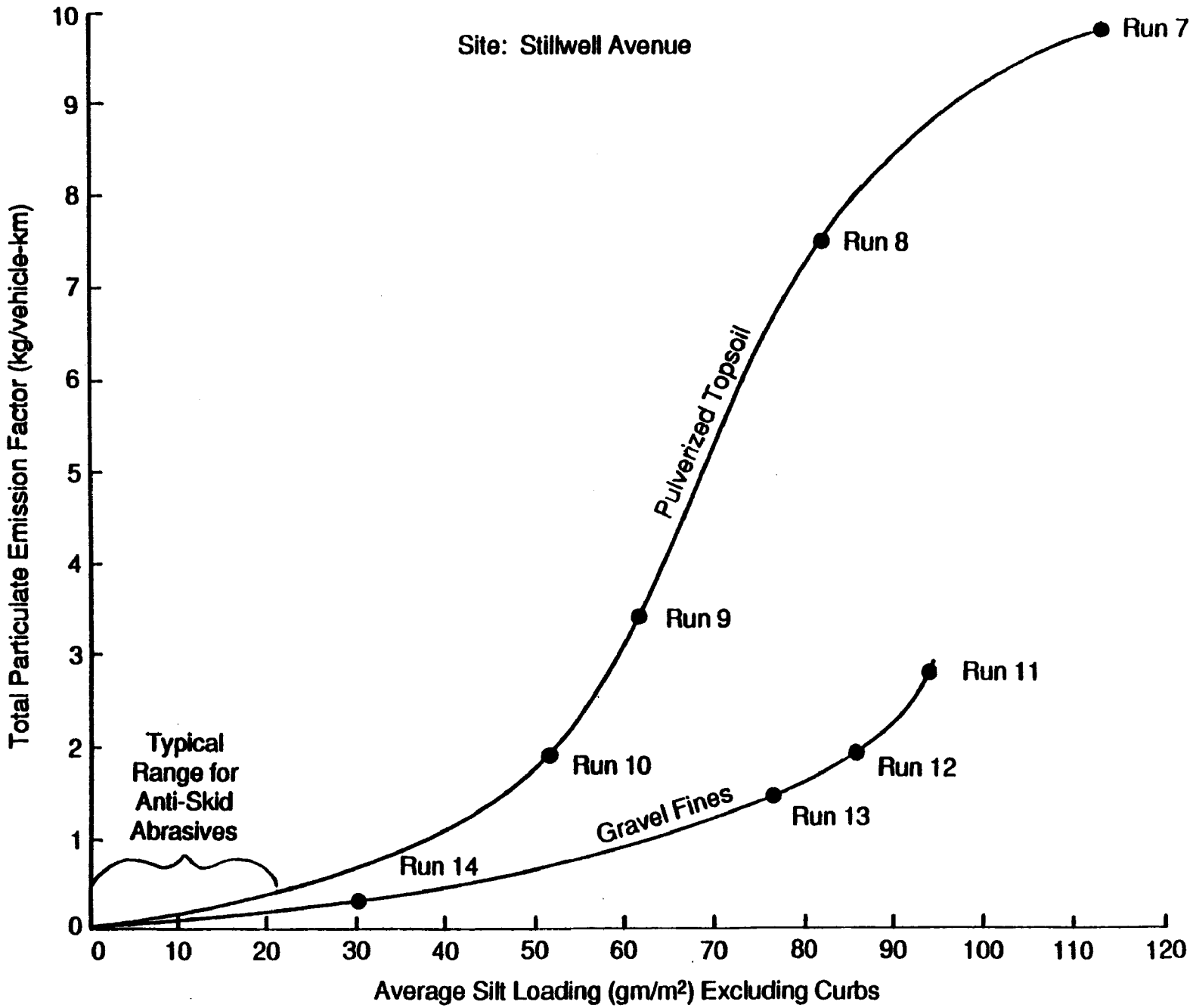

Figure 1-1. Total particulate emission factor vs. average silt loading for an artificially loaded paved road.

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 the 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 applied 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 control programs that encompass improvements in three potential 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 followed by broom sweeping has proven to be most effective in capturing silt-sized particles present in paved road surface material.

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 which produces fewer PM_{10} emissions. Thus the primary purpose of this study is to provide guidance on methods to determine: (a) the durability and initial silt content of antiskid material selected for use on ice- and snow-covered roadways; and (b) criteria for defining the elements of an effective PM_{10} emission control strategy associated with use of antiskid materials.

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 of target states and municipalities especially 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.

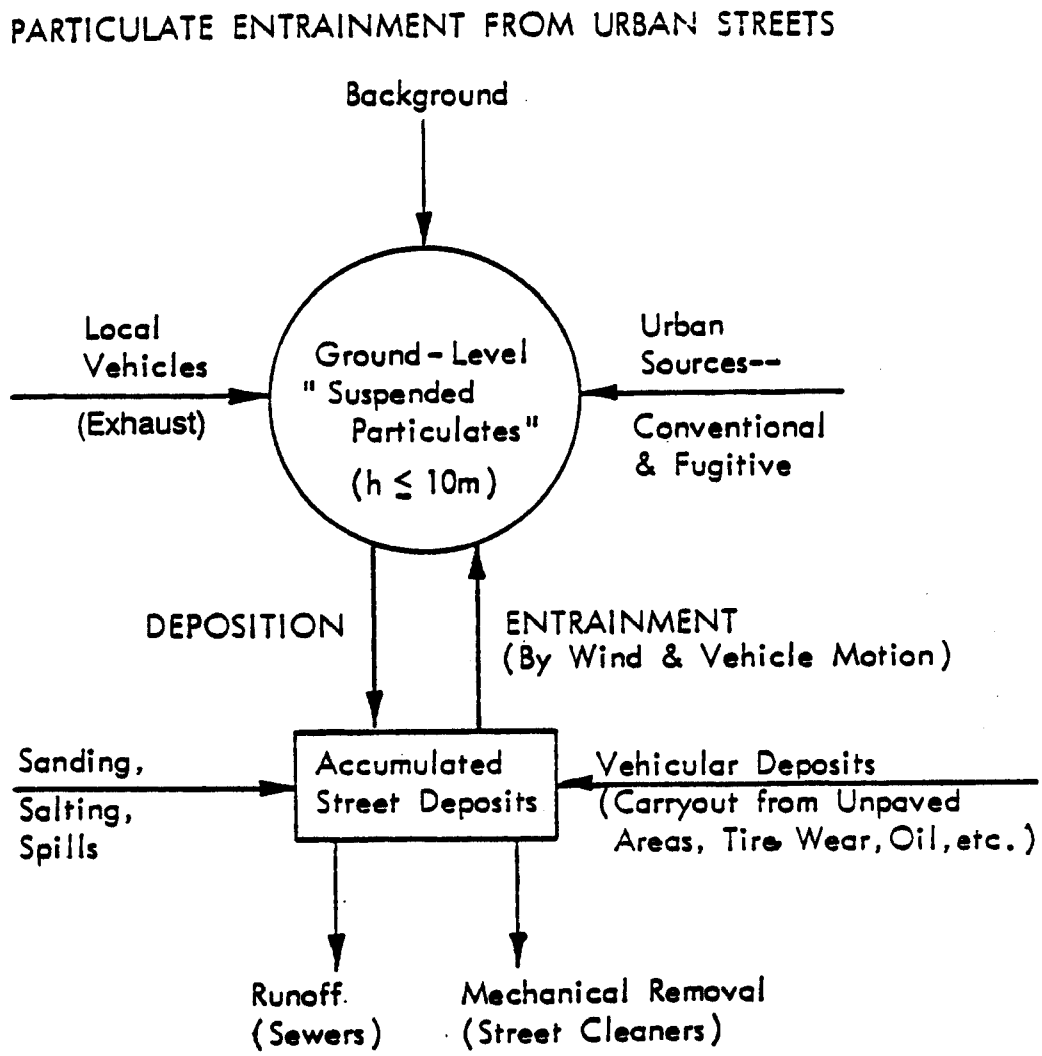

Figure 1-2. Diagram of street surface/atmospheric exchange of particulate matter.

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," following American Society for Testing and Materials definitions.

5. Fine aggregate: aggregate passing the three eighths (3/8) inch sieve and almost entirely passing the No. 4 (4.75 millimeter [mm]) sieve and predominantly retained on the Number 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 the measurement methods for the physical properties of antiskid materials.
- Section 4 reviews alternative skid control measures.
- Section 5 develops the rationale for selection of effective antiskid materials.
- Section 6 presents the conclusions and recommendations derived from this 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.

Example abrasives include sand and cinders which provide a gritty surface for traction 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) and calcium chloride.

Eleven states and municipalities were questioned 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.

This section documents results from the literature review, a current and relevant survey 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 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 exclusively. Higher proportions of salt to sand were used in urban areas while lower proportions were applied in rural areas where traffic intensities are less. Agencies typically reported their selection of antiskid materials was based on what was available, presumably at reasonable cost.

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	NS	No specification	NS	--
	Crushed pit	NS			
	Crushed quarry	NS			
	Screened cinders	NS			
	Quarry cinders	NS			

(continued)

TABLE 2-1 (Continued)

State/city	Types of material	Cost ($)	Abrasives (maximum % < 200 mesh)	Sieving method	Comments
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.
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 (> 1/2")	NS NS NS NS	10 < 100 mesh - - 10	NS	Unit weight tested for, but no specifications.

(continued)

TABLE 2-1 (Continued)

State/city	Types of material	Cost ($)	Abrasives (maximum % < 200 mesh)	Sieving method	Comments
Nebraska	Screened pit	NS	6	NS	No crushed material.
	Boiler slag	NS			
Nevada	Screened pit	NS	8	NS	--
New Hampshire	Screened pit	NS	12 < 4 mesh	NS	Must be washed; sharp "feel" desirable.
	Washed sand	NS			
New Jersey	Salt				No sand used because of clogging of inlets and drainage, and motorist safety.
New York	Pit run	4.25/ton sand	5	New York DOT	
	Screened pit	NS		703-1P	Must be free of too much clay, loam, etc.;
	Crushed pit	NS		703-2P	particles must not degrade in service and must visually contrast with ice/snow.
	Crushed quarry	NS			
	Iron ore tailings	NS			
	Crushed slag	NS			
	Crushed cinders	NS			
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.

(continued)

TABLE 2-1 (Concluded)

State/city	Types of material	Cost ($)	Abrasives (maximum % < 200 mesh)	Sieving method	Comments
Utah	NS	NS	10 or 15	AASHTO T-11	Portion through No. 40 sieve shall be non-plastic 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.
	Crushed quarry	NS			Low fines present fewer problems with water retention and plugging.
	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.
	Crushed pit	NS			Free of organic material.

NS = Not specified.

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 μm 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).

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

Nominal Aperture Width Microns	Nominal Aperture Width Inches	U.S. Standard	Nominal Aperture Width Microns	Nominal Aperture Width Inches	U.S. Standard
1	.00004	12500	297	.0117	50
2.5	.0001	5000	350	.0138	45
5	.0002	2500	420	.0165	40
10	.0004	1250	500	.0197	35
20	.0008	625	590	.0232	30
37	.0014	400	710	.0280	25
44	.0017	325	840	.0331	20
53	.0021	270	1000	.0394	18
62	.0024	230	1190	.0469	16
74	.0029	200	1410	.0555	14
88	.0035	170	1680	.0661	12
105	.0041	140	2000	.0787	10
125	.0049	120	2380	.0937	8
149	.0059	100	2830	.111	7
177	.0070	80	3360	.132	6
210	.0083	70	4000	.157	5
250	.0098	60	4760	.187	4

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 the fines are removed. Fines are described as those particles passing a No. 50 sieve. Table 2-3 provides desirable characteristics of anti-skid abrasives (Schneider, 1959).

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

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 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 become liquid 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 material 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. Little 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, 1988). No field data were available for validation of this estimate.

The sodium chloride content of rock salt is about 99% for salt mined in Louisiana, 98% for New York and Michigan, and 94% to 98% for Kansas salt. 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 purer than larger particles.

Kaufman (1968) noted that anhydrite bonds in rock salt deposits are "tougher, harder, or have a stronger crystal intergrowth than the purer salt between the bonds. The net result is that the purest salt gravitates toward the finer sizes, although the tendency may reverse in the very finest screenings, which contain relatively large concentrations of anhydrite grains." Anhydrite (calcium sulfate), the major impurity, 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 (Kaufman, 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.

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: Kaufman (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: Kaufman (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.

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 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 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 Section 4.

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.

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° -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 ploughing 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 travelling at high speed.
Abrasives	Increase sliding friction immediately.		Improve skid resistance immediately.	As listed for other abrasives. Easily brushed off the road by tires.

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).

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).

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

Agency	Year	Annual totals NaCl (tons)	$CaCl_2$ (tons)	Sand (tons)	Other	Tons/ lane mile	Application rates
States							
California	69/70	22,000					400-600 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							500-1,000 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				600-800 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				100-300 lb/lane mile

(continued)

TABLE 2-7 (Continued)

Agency	Year	Annual totals NaCl (tons)	$CaCl_2$ (tons)	Sand (tons)	Other	Tons/ lane mile	Application rates
Nebraska	72/73	18,000	800				200-500 lb/2-lane mile
Nevada							0.5 yd^3/2-lane mile
New Hampshire	69/60	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				150-500 lb/lane mile
New York	69/70	192,384	2,285				200-600 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	
Oregon	6970	810	180				
	70/71	710	260				
	71/72	720	None				
Pennsylvania	69/70	565,750	26,500				400 lb/lane mile max. 60-80 lb/Type 1 $CaCl_2$/ton sand
	70/71	738,800	31,100				
	71/72	652,500	29,550				
South Dakota	71	1,536	323	40,507			300-500 lb/2-lane mile
	72	1,890	368	43,400			
	73	2,804	380	46,400			
Vermont	69/70	110,000				21.1	300-800 lb/2-lane mile; 546 lb/2-lane mile (average)
	70/71	88,000				16.3	
	71/72	97,000				17.6	
	72/73	88,260				16.0	

(continued)

TABLE 2-7 (Continued)

Agency	Year	Annual totals NaCl (tons)	$CaCl_2$ (tons)	Sand (tons)	Other	Tons/ lane mile	Application rates
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°-32°F: 200-250 lb/lane mile NaCl; 10°-25°F: 250-300 lb/lane mile 3:1 NaCl-$CaCl_2$; < 10°F: 350-450 lb/lane mile $CaCl_2$ flake or 300-375 lb/lane mile $CaCl_2$ pellet
	71/72	15,251					
	72/73	16,665					
West Virginia	69/70	152,453	10,045				500-600 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)					100-300 lb/lane mile
H.S.	69/70	59,448				7.1	300-600 lb/2-lane mile; 70/71 ave.: 490, 71/72 ave.: 450
	70/71	121,328				13.9	
	71/72	145,755				15.4	
Ontario	70/71	363,264					Sand: 2,000 lb/ 2-lane mile; salt: 450 lb/2-lane mile
	71/72	419,137					
	72/73	336,959					

(continued)

TABLE 2-7 (Concluded)

Agency	Year	Annual totals NaCl (tons)	$CaCl_2$ (tons)	Sand (tons)	Other	Tons/ lane mile	Application rates
Toll Roads							
Illinois State Toll Highway Authority		44,000	691	7,740			500-600 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
	70/71	27,162	1.363		29,498		200 lb/mile of 2:1 $NaCl-CaCl_2$ for freezing rain
	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					100-450 lb/lane mile
	70/71	43,257					
	71/72	38,940					
New York City	70/71	128,928					2 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)

State	Total lane miles	Bare pavement miles	Winter 1981-1982				Winter 1982-1983			
			Salt (tons)	Calcium chloride Dry (tons)	Calcium chloride Liquid (gal)	Abrasives (tons)	Salt (tons)	Calcium chloride Dry (tons)	Calcium chloride 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

(continued)

TABLE 2-8 (Continued)

State	Total lane miles	Bare pavement miles	Winter 1981-1982 Salt (tons)	Winter 1981-1982 Calcium chloride Dry (tons)	Winter 1981-1982 Calcium chloride Liquid (gal)	Winter 1981-1982 Abrasives (tons)	Winter 1982-1983 Salt (tons)	Winter 1982-1983 Calcium chloride Dry (tons)	Winter 1982-1983 Calcium chloride Liquid (gal)	Winter 1982-1983 Abrasives (tons)
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
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

(continued)

TABLE 2-8 (Continued)

State	Total lane miles	Bare pavement miles	Winter 1981-1982 Salt (tons)	Winter 1981-1982 Calcium chloride Dry (tons)	Winter 1981-1982 Calcium chloride Liquid (gal)	Winter 1981-1982 Abrasives (tons)	Winter 1982-1983 Salt (tons)	Winter 1982-1983 Calcium chloride Dry (tons)	Winter 1982-1983 Calcium chloride Liquid (gal)	Winter 1982-1983 Abrasives (tons)
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
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

(continued)

TABLE 2-8 (Concluded)

State	Total lane miles	Bare pavement miles	Winter 1981-1982 Salt (tons)	Winter 1981-1982 Calcium chloride Dry (tons)	Winter 1981-1982 Calcium chloride Liquid (gal)	Winter 1981-1982 Abrasives (tons)	Winter 1982-1983 Salt (tons)	Winter 1982-1983 Calcium chloride Dry (tons)	Winter 1982-1983 Calcium chloride Liquid (gal)	Winter 1982-1983 Abrasives (tons)
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
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)
7/77-6/78	10,927
7/78-6/79	11,323
7/79-6/80	8,108
7/80-6/81	7,240
7/81-6/82	9,787
7/82-6/83	7,267
7/83-6/84	10,329
7/84-6/85	10,730
7/85-6/86	11,057
7/86-6/87	9,462
7/87-6/88	11,147
7/88-6/89	10,181

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 300-800 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 200-400 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 600-800 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 500-600 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 1500 to 2000 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.

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 of sand 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, 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 covered 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 of the material. Regular 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) reported that salted roads were dirtier than sanded ones. Glass plates attached to the rear bumpers of cars were used to collect samples. After exposure of the glass plates while driving on wet roadways, light transmission through the plates was measured to give a semi-quantitative estimate of the comparative dirtiness of the roads.

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

Weather conditions			Application rate (pounds of material per mile of 2-lane road or 2-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

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 their urban roads with vacuum sweepers. Their cleanup operations begin in late February to keep strong spring winds from picking up the remaining sand on roadways causing a sandblasting action. Wyoming, 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.

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 C.

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.

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, 1981; 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

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

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 D. The approximate 1989 cost of an 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 (r^2) 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 (r^2) 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, 1979). 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 E.

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 petrographic 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.

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 150-300 um 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

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 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 16-18 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 tests is not directly related to aggregate durability, however.	$600 (50 cycles)	1
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

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]
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 = 1985 Annual Book of ASTM Standards, American Society of Testing and Materials, Philadelphia, Pennsylvania, 1985.
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.

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. The significance of this should be obvious.

3.4 MEASUREMENT METHODS FOR DEICING CHEMICALS

Rock salt used for road deicing purposes is comprised mostly of NaCl which does not 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 temporarily 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 $CaSO_4$, 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, 50 g of sample is placed in 200 mL of water and stirred for a period of 5 min (Kaufmann, 1968). 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).

SECTION 4

ALTERNATIVE SKID CONTROL MEASURES

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.

4.1 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 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. 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 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 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 4-1 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 4-1. 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	1-1/2 to 2 times as much required for same effect
		5 to 10 times as 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 out performs 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.

4.2 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 4-1 from Minsk (1981) and in Table 4-2 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 geo-thermal 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.

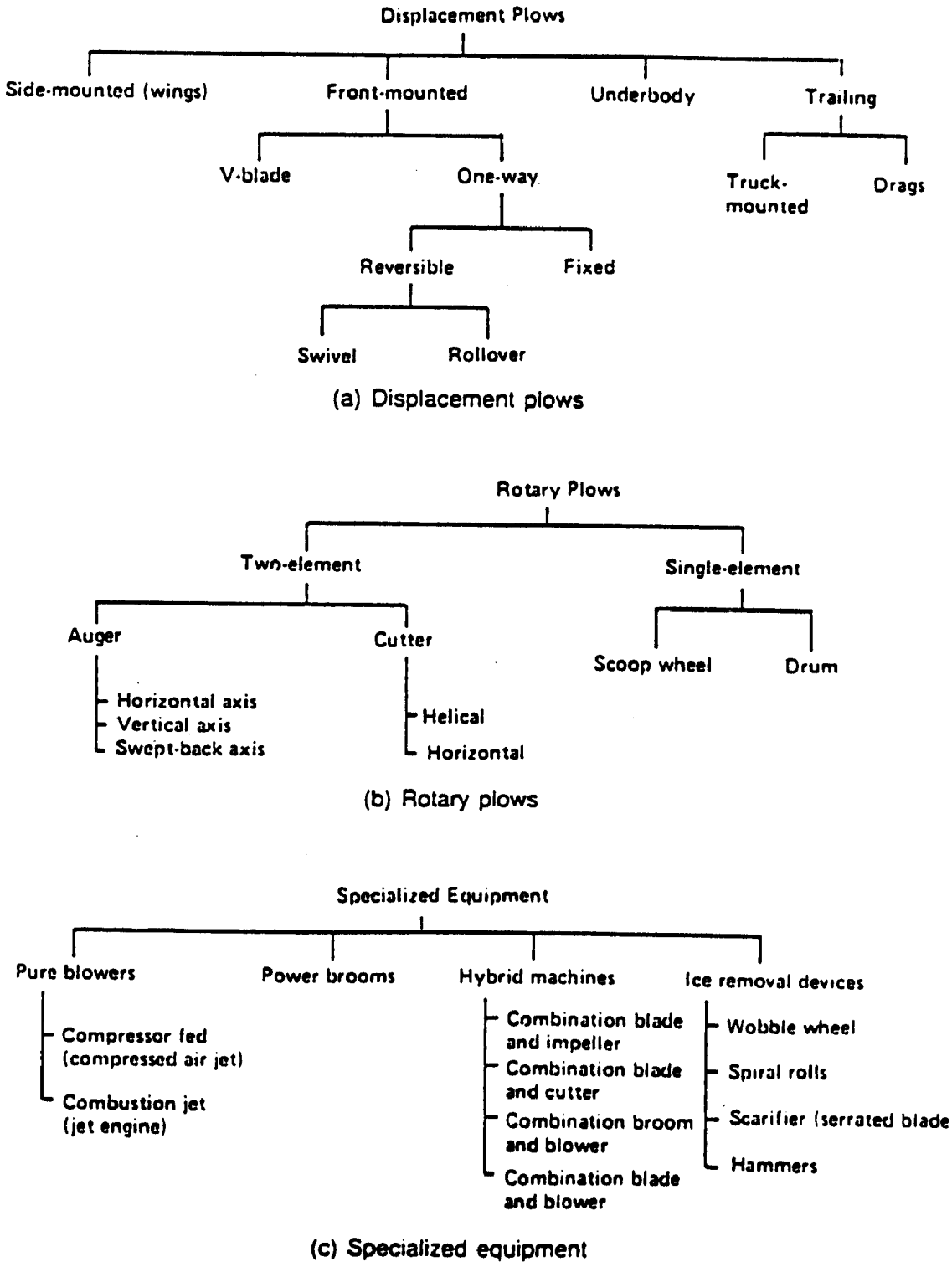

Figure 4-1. Family tree of snow removal equipment (Minsk, 1981).

TABLE 4-2. 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 4-3. 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.

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.

TABLE 4-3. RATING OF CONCEPTS FOR ALTERNATIVE PHYSICAL DEICING METHODS (BLACKBURN, 1978)

Concept	Category rating values[a]										Overall rating values[a] (average)	
	Technical feasibility		Operational feasibility maintenance operations		Operational feasibility traffic operations and safety		Economic acceptability		Environmental acceptability			
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
• 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

(continued)

TABLE 4-3 (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)	
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.

One of the most promising concepts was actually tested by Blackburn--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.

SECTION 5

SELECTION CRITERIA

In this section, criteria for selecting appropriate materials for use in ice and snow control will be presented as a guide to regulatory personnel. The following sections discuss the potential of antiskid materials to generated PM_{10}, its effectiveness and durability in service, and applicable cost data related to both traditional abrasives and deicers as well as alternative skid control measures (e.g., embedded pipe pavement heating). Finally, minimum acceptability criteria for material selection will be provided in the form of a decision tree.

5.1 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 the report of that particular study had not as yet been issued at the time of this analysis.

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 5-1.

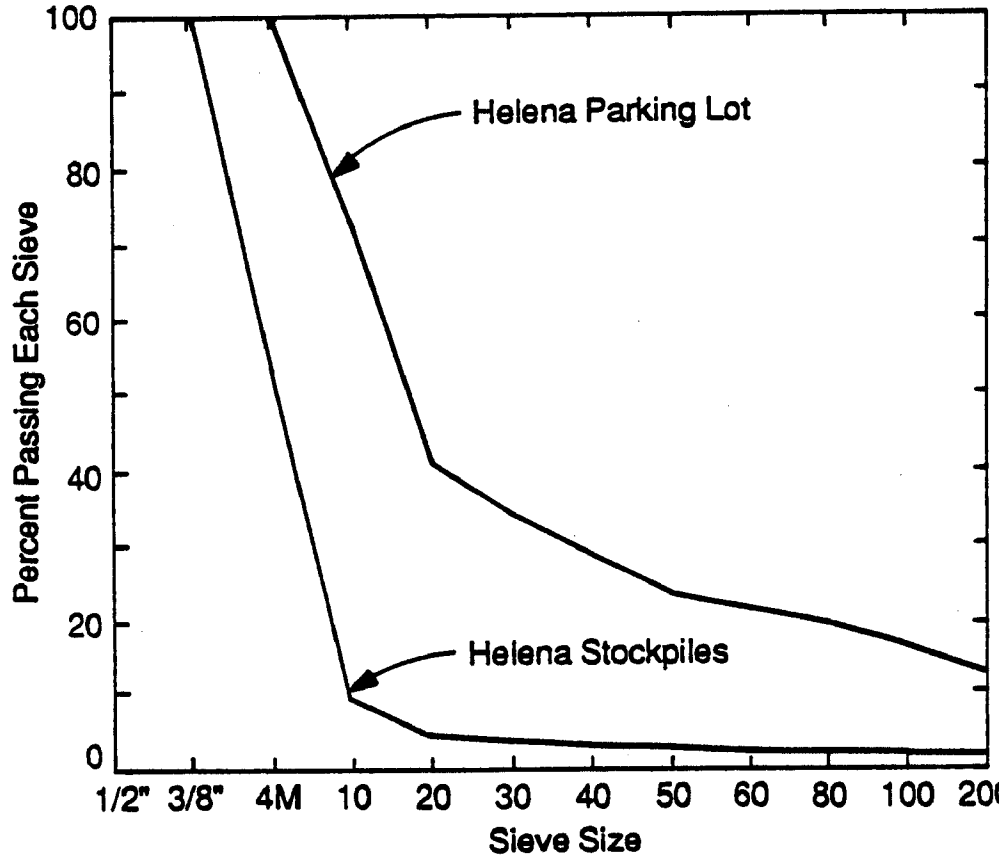

Figure 5-1. Sieve analysis data of antiskid material in Helena parking lot.

As can be seen from Figure 5-1, the percentage of material less than 200 mesh 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, 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 5-2 with the exposure profiling results for total particulate shown in Figure 5-3.

As shown by Figure 5-2, 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 exposure profiles in Figure 5-3.

The final data set located during the literature search is from the original salting and sanding demonstration study performed in Denver during the winter of 1980-1981 (PEDCo, 1981). In this study, 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 both with and without poststorm street cleaning. Application rates or properties of the antiskid materials used in the study were not specified.

From a review of the data collected during the Denver program, it was determined that neither data set showed much correlation of air quality measurements with either the application of different antiskid materials or for poststorm cleaning. However, the data from the Lakewood study area were found to be somewhat useful in defining general trends for the current program.

Figure 5-4 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 5-5 shows a similar plot for silt loading. Finally, Figure 5-6 provides air quality measurements for TSP as determined at the near-street monitoring site.

As indicated by these figures, the data show a high degree of scatter indicating the influence of outside factors not associated with application of the antiskid materials. However, for sand application there is some evidence of air quality improvement that can be associated with an apparent decay in silt loading during the period following sand application.

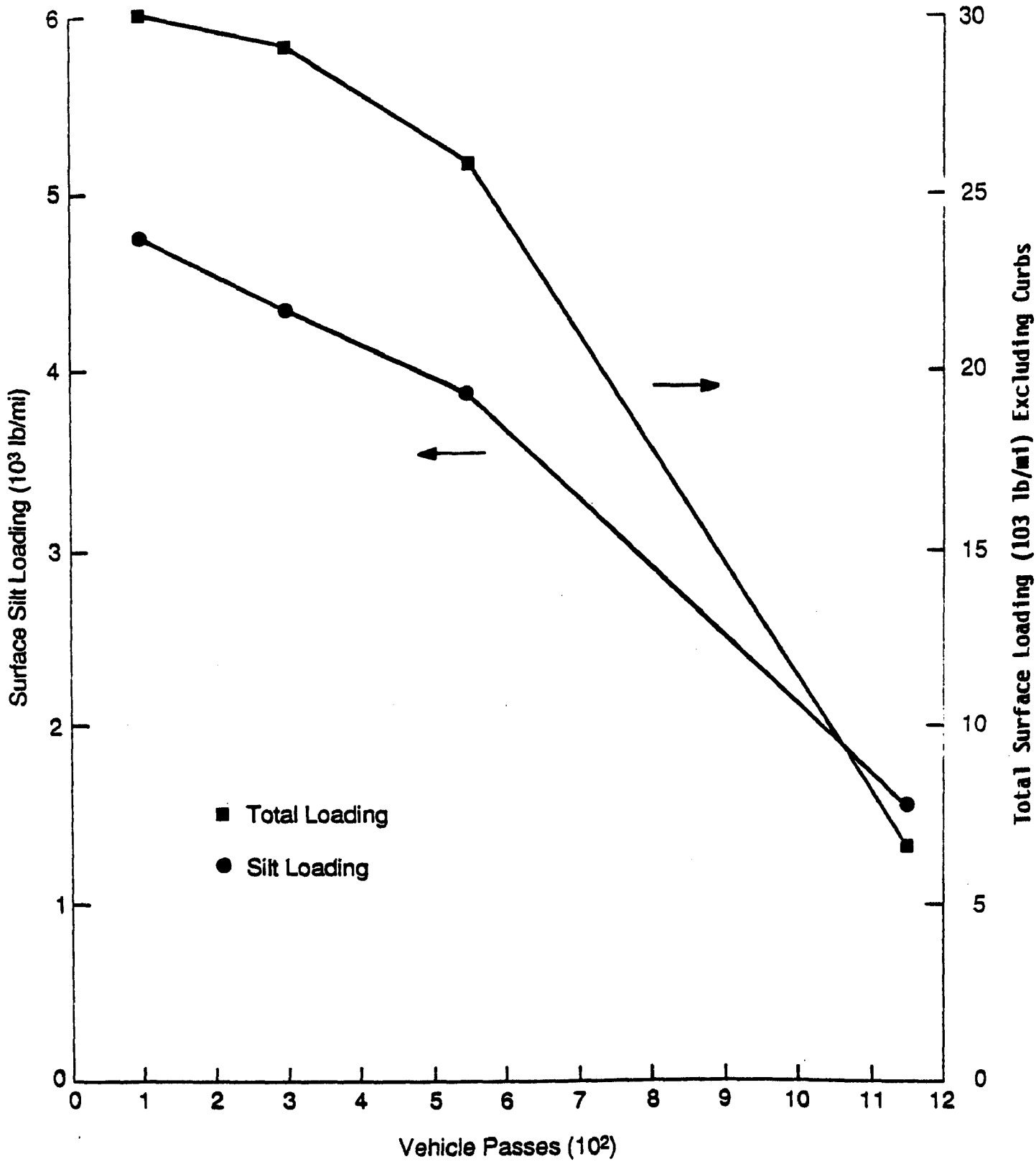

Figure 5-2. Total loading and silt loading vs. number of vehicle passes for artificially loaded paved road.

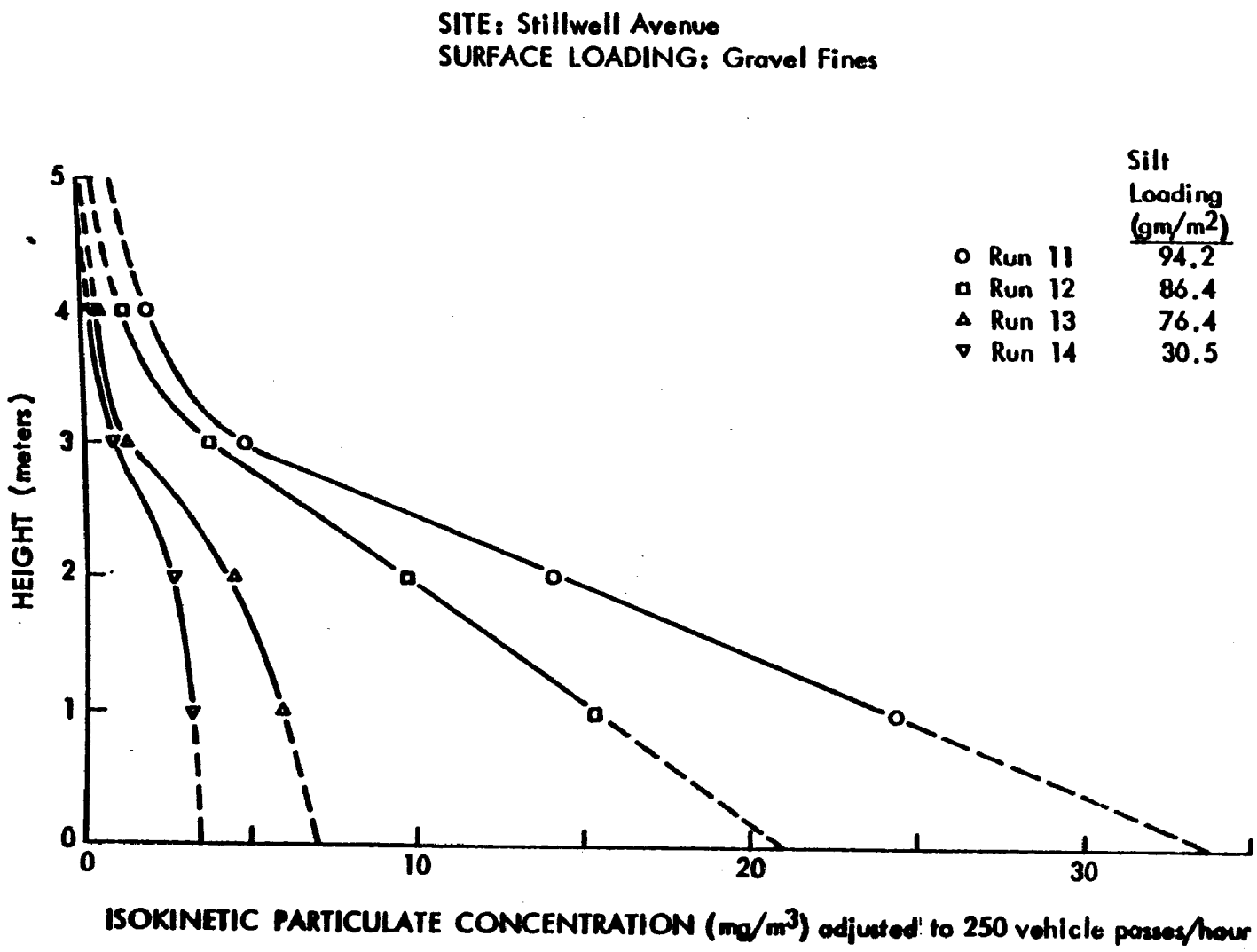

Figure 5-3. Exposure profiles of total particulate concentration for artificially loaded paved road.

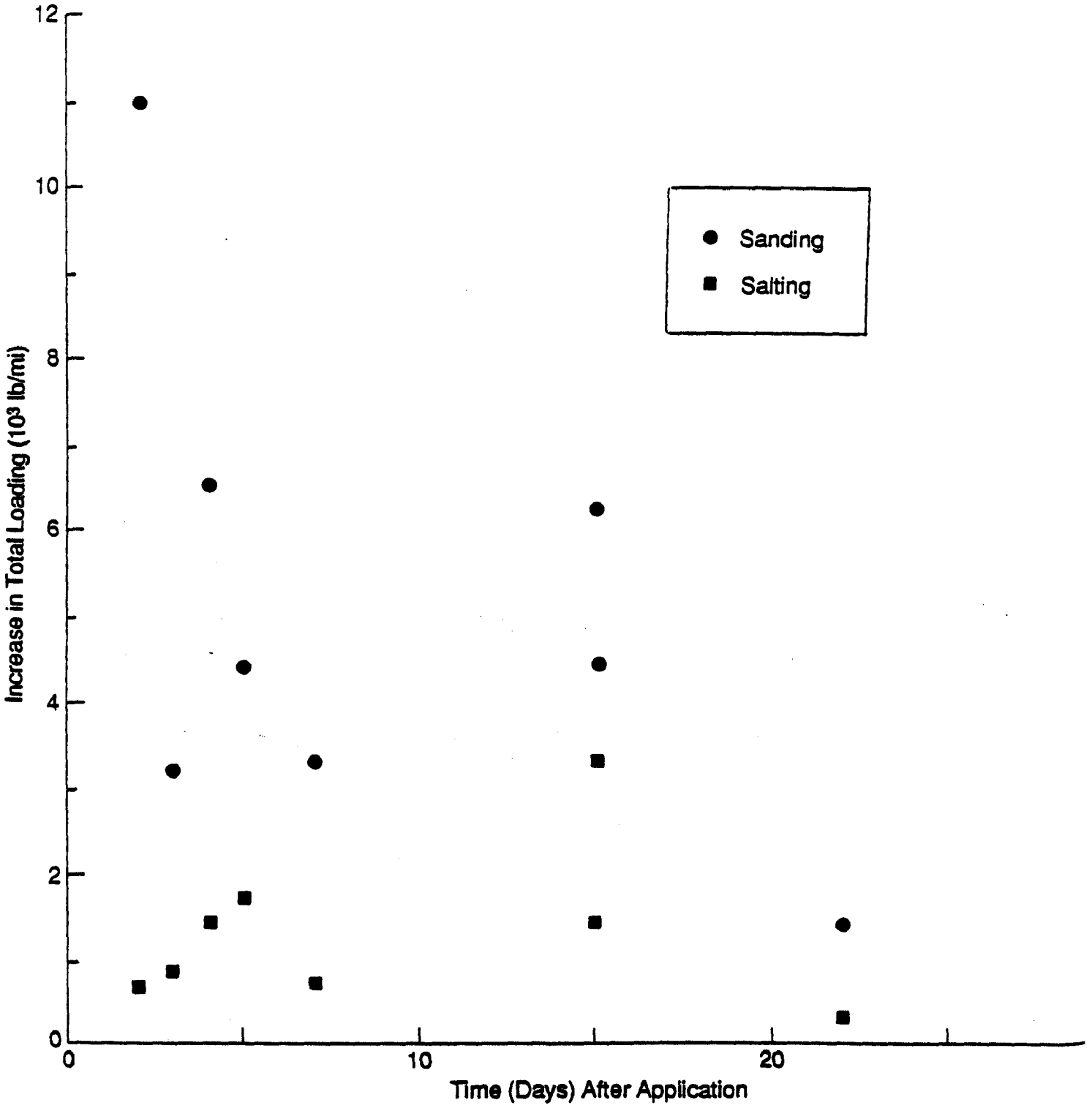

Figure 5-4. Increase in total surface loading vs. time after application of salt or sand.

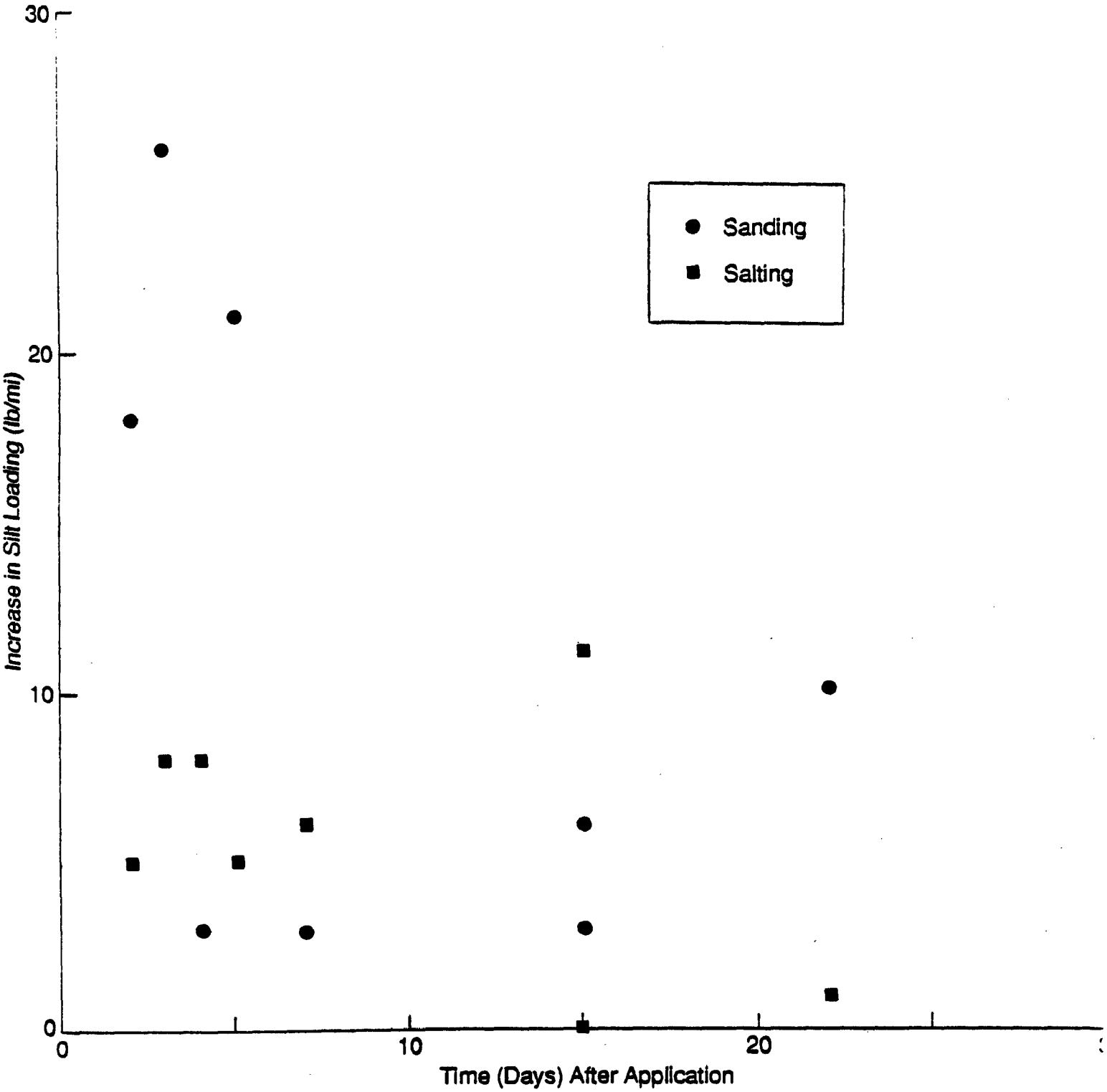

Figure 5-5. Increase in silt loading vs. time after application of salt or sand.

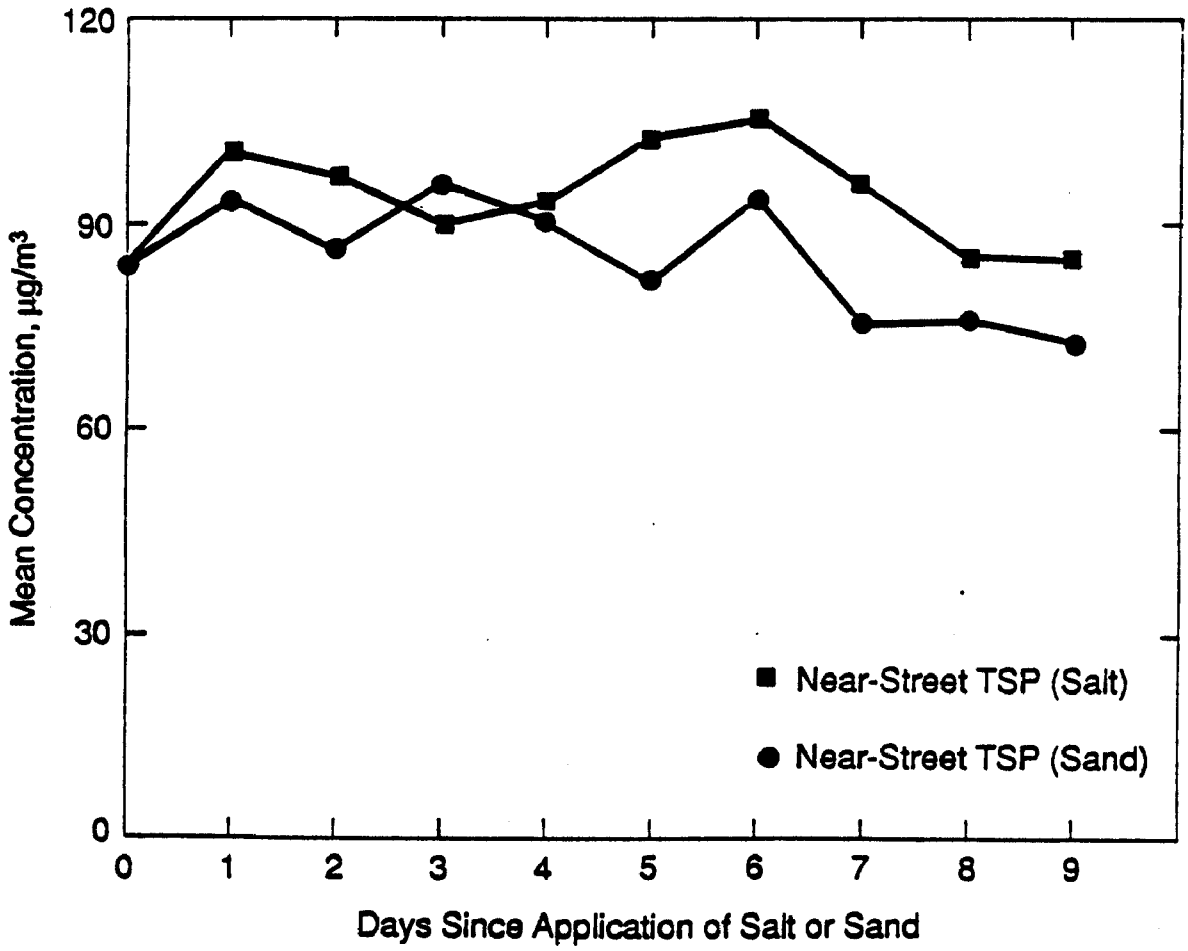

Figure 5-6. TSP air quality impact of salt and sand application over time.

5.2 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 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:

$$F = f \times P \tag{5-1}$$

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/hr). The measurements are reported in terms of skid number (SN) which is computed as follows:

$$SN = 100\ f = 100\ T_f/L \tag{5-2}$$

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 house 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/ft². The test results for the friction measurements conducted are shown in Figure 5-7 (on an equivalent volume basis) and the results of impact tests shown in Table 5-1.

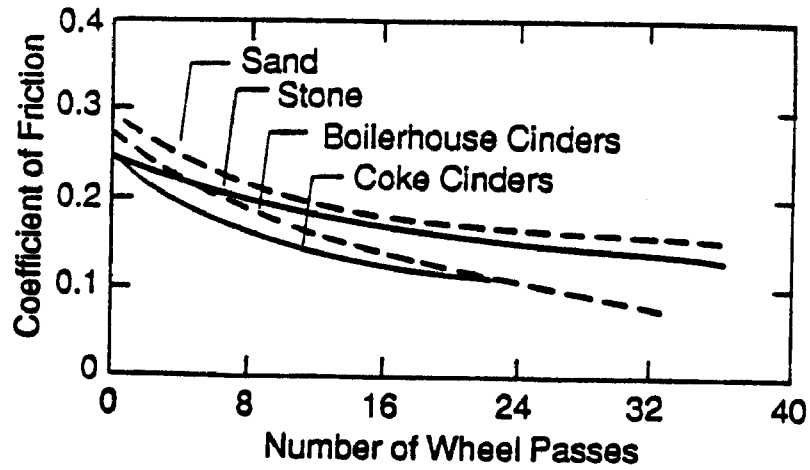

Figure 5-7. Coefficient of friction (f) vs. number of wheel passes for four antiskid materials compared on an equal volume basis.

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 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 5-8 which show the skid resistance of limestone material 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.

TABLE 5-1. RESULTS OF IMPACT TESTS

Type of material	Percent breakdown*
Boiler cinders	5.3
Coke cinders	3.9
Natural sand	0.7
Limestone	0.8

* 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.

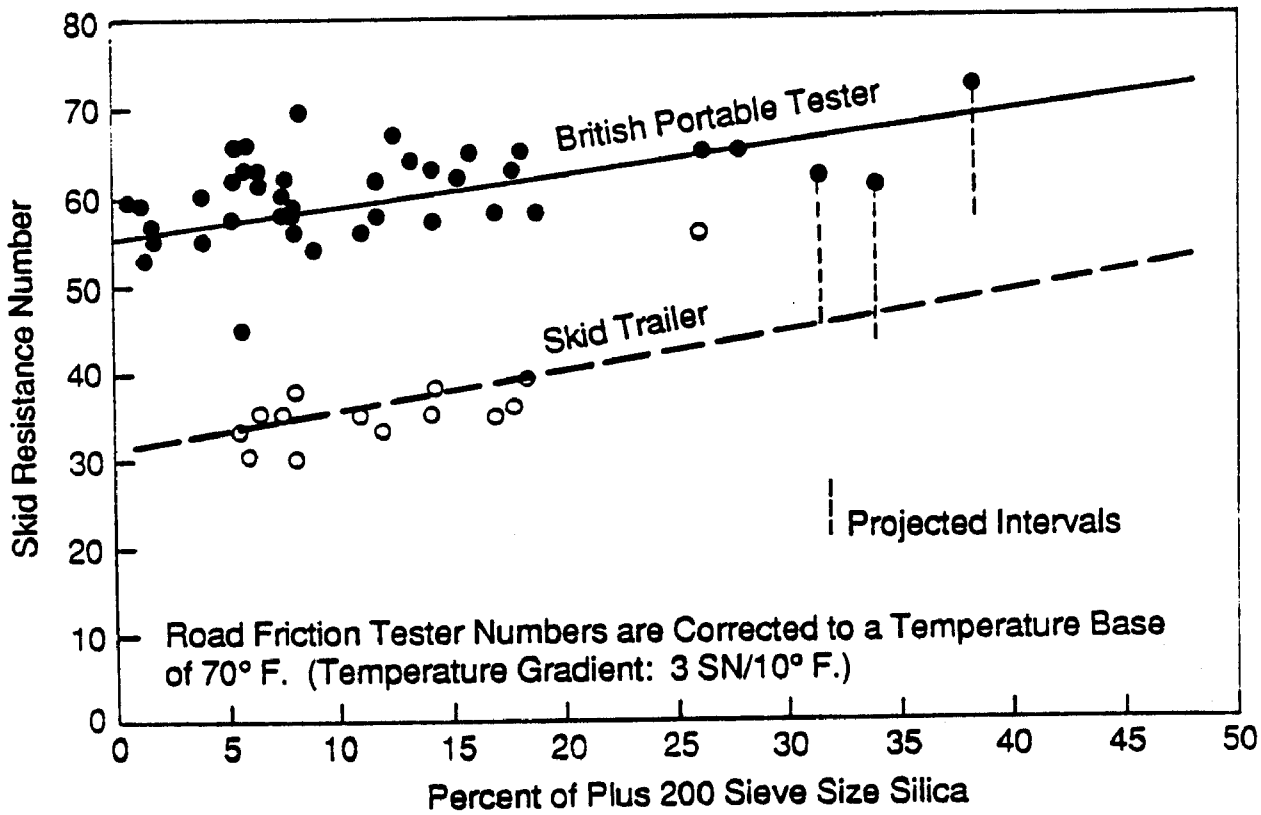

Figure 5-8. Skid resistance of limestone material vs. percent +200 mesh silica (Furbush, 1972).

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 5-2. Representative data for these tests are shown in Figures 5-9, 5-10, and 5-11 for the cold room and vehicular tests, respectively, at various application rates.

TABLE 5-2. 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 5-9, 5-10, and 5-11, 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.

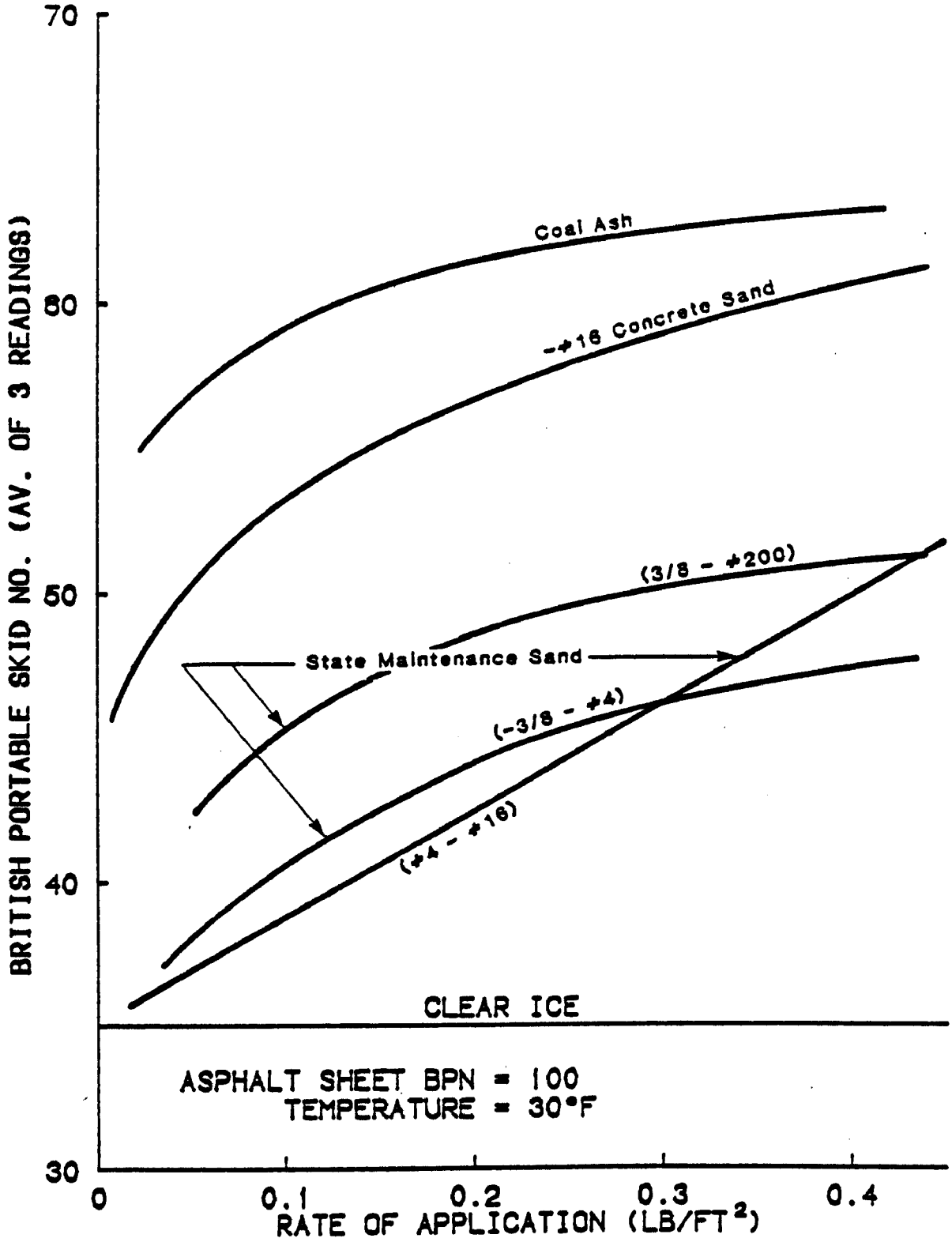

Figure 5-9. Average British portable skid number vs. rate of aggregate application for various antiskid materials (30°F).

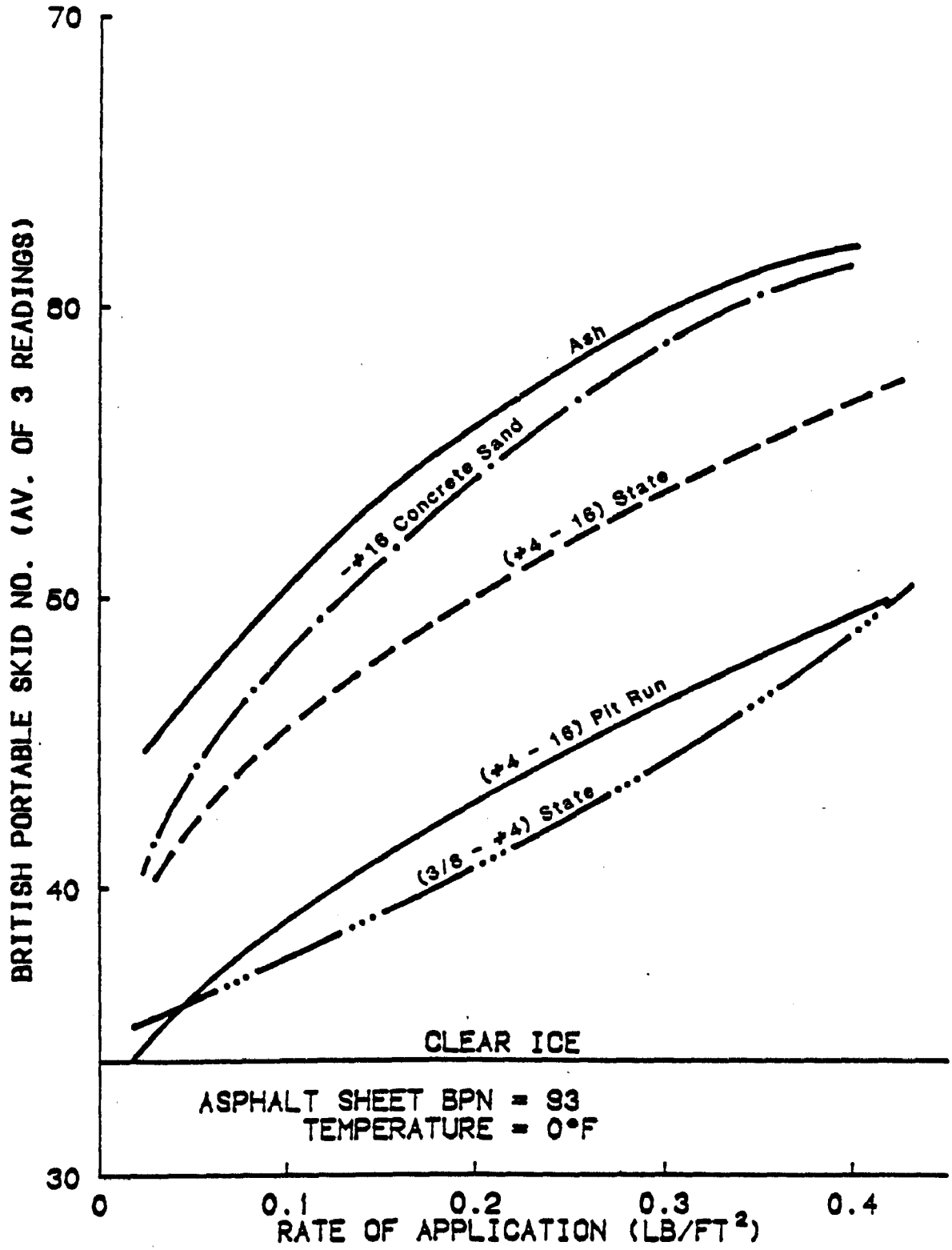

Figure 5-10. Average British portable skid number vs. rate of aggregate application for various antiskid materials (0°F).

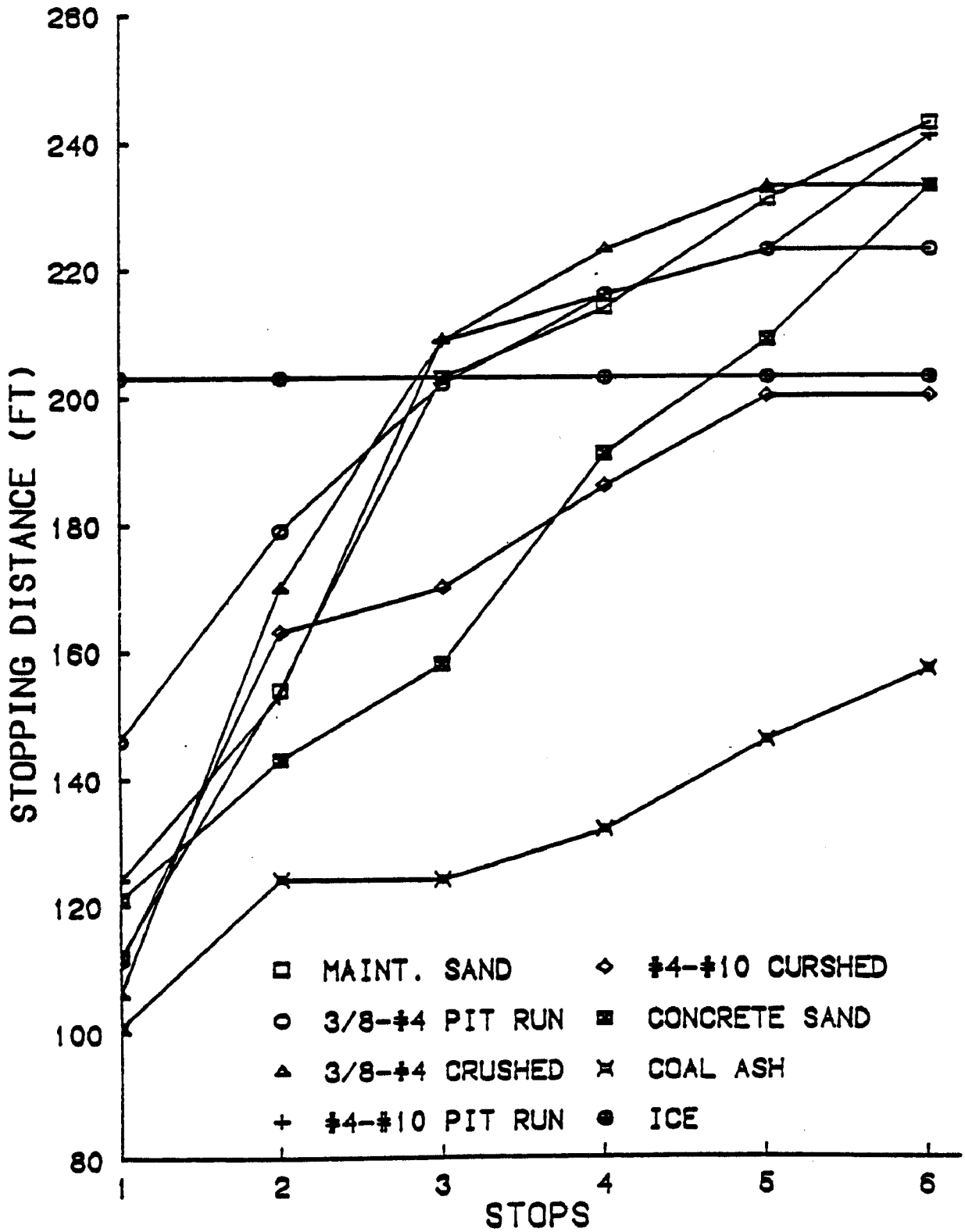

Figure 5-11. Average stopping distances determined on an ice track for various antiskid materials.

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

5.3 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.

5.3.1 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 Vicker's hardness. For minerals softer than the abrasive, this relationship was:

$$d > \frac{E\ S}{Y_s^2} \sim Hv^{-3/4} \qquad (5\text{-}3)$$

where:
- d = Diameter of the wear particle (or volume removed)
- E = Modulus of elasticity (psi)
- S = Surface energy of the formed particle
- Ys = Mineral yield stress (psi)
- Hv = Vicker's hardness (kg/mm^2)

For minerals harder than the abrasive the relationship is:

$$d > \frac{E\ Hv^{1/3}}{Y_s^2} \tag{5-4}$$

where the terms are as defined above. The average data collected in the study are shown in Table 5-3.

As shown by the data in Table 5-3, the amount of wear is inversely proportional to the hardness of the mineral. This is illustrated in Figure 5-12 for different minerals abraded with SiO_2. These data would suggest that an antiskid abrasive with a Vickers hardness > ~ 1,000 kg/mm² 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.

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.

5.3.2 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).

TABLE 5-3. AVERAGE MINERAL WEAR FOR DIFFERENT ABRASIVE TYPES

Mineral	Melt temp. (°C)	Modulus (psi x 10^6)	Yield stress (psi x 10^4)	Specific gravity	Vicker's hardness (kg/mm²)	Abrasive wear (mm³ 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] Crystal-like with cleavage planes.

[b] Limestone chips.

[c] Clear fused-quartz rod.

[d] Glass-like lump.

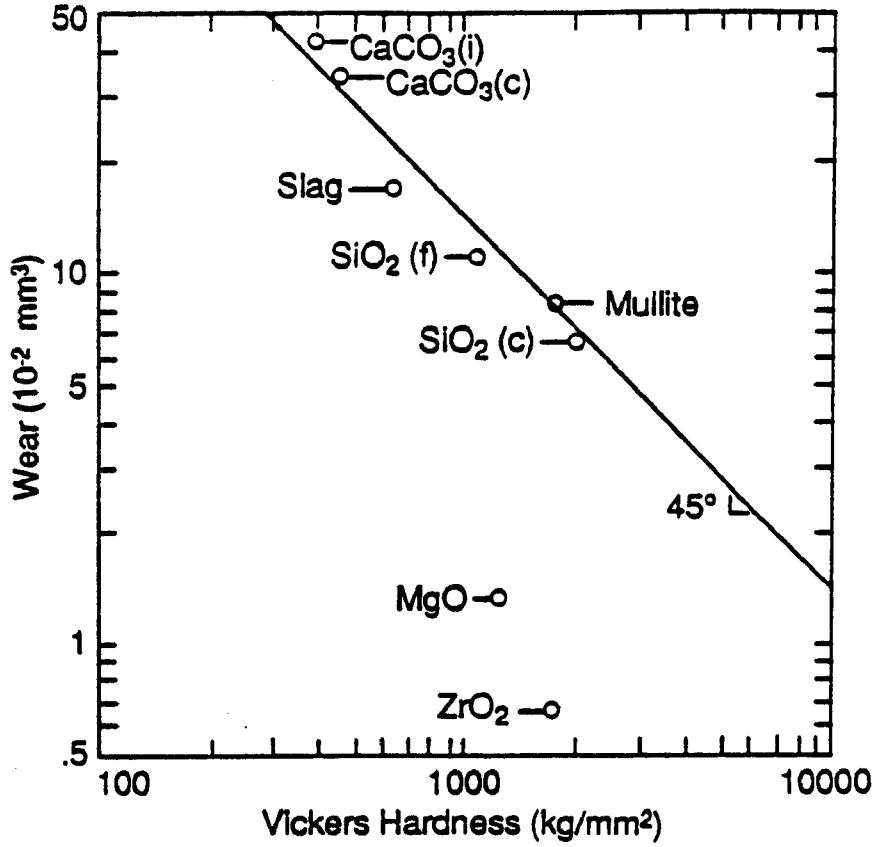

Figure 5-12. Mineral wear rate vs. Vicker's hardness for SiO_2 abrasive.

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 at least a Group III material (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.)

5.3.3 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 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. Using an IBM compatible computer and LOTUS software, the regression equation determined was:

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

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 which would indicate that all six strength parameters are highly intercorrelated with the Los Angeles abrasion value. Thus, these data would indicate that a single test can be used as the overall measure of aggregate durability which considers impact, crushing, soundness (i.e., freeze/thaw resistance), flakiness, water absorption, and specific gravity. It is therefore recommended that any future field sampling of antiskid materials 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.

5.4 COST EFFECTIVENESS

5.4.1 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 5-4.

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.

5.4.2 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 5-5 and 5-6 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.

TABLE 5-4. 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 5-5. 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 5-6. 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.

5.4.3 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 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 5-7 illustrates approximate costs of corrosion and environmental damages due to deicing salts.

5.4.4 General Cost Considerations

As can be observed by comparing Tables 5-5 and 5-6, 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 5-7. 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.

5.5 ACCEPTABILITY CRITERIA

Based on the evaluation of information obtained in this study, general selection criteria have been developed for antiskid materials that have a low target potential for silt generation in service. For example, these criteria can be met by washed construction aggregates (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 guidelines pending further laboratory and field evaluations (see Section 6.2). The acceptability criteria derived from available data are shown in Table 5-8.

TABLE 5-8. 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
	Vicker's hardness	> 1,000 kg/mm^2
	Fracture	> 80%
	Void fraction	> 50%
	Quartz content	> 90%
Salts	Percent insoluble matter	< 2%

Development of comprehensive selection criteria for deicing compounds (salts) requires further investigation of emissions potential for such compounds. Although the temperature ranges for effective use of these compounds are known, basic information is lacking on the portions (soluble and insoluble) which are available for resuspension from the roadway surface exposed to traffic.

As a further guide to regulatory and transportation personnel, a decision "tree" has been developed for material selection as shown in Figure 5-13. 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 5-8 and the decision tree shown in Figure 5-13 should assist in the overall selection process.

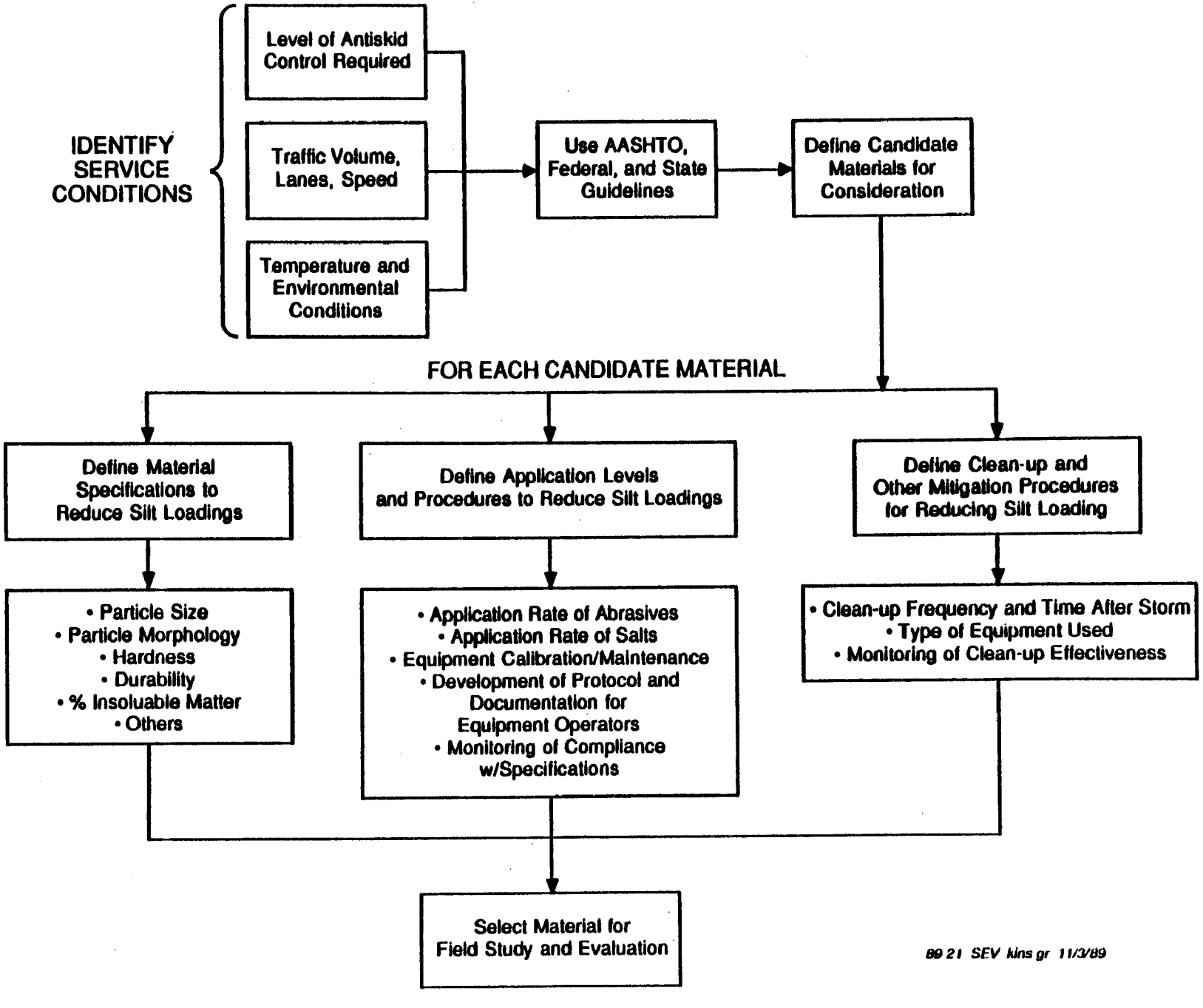

Figure 5-13. Decision "tree" for antiskid material selection

SECTION 6

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.

6.1 CONCLUSIONS

The following conclusions were reached as part of this study:

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) are 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) is 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 (but 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 non-

compliance with recommended fines and durability specifications for antiskid abrasives.

6.2 RECOMMENDATIONS

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

1. A modified Los Angeles abrasion test method should be developed to determine the silt generation potential of antiskid abrasives.

2. The current method for 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.

4. Further study of the fate and transport of salt(s) applied for antiskid control is needed to determine the salt forms (soluble and insoluble) contributing to PM_{10} emissions.

5. Common poststorm 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.

SECTION 7

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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 online 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 size 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 7 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: _____

(9/8/89)

Figure A-1 (Concluded)

SD:DOT
Sanding Materials Questionnaire Agency: _____

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

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

(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

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APPENDIX C

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).

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[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 solids over the nested sieves, arranged with the coarser sieve on top. Take care to avoid, as much as feasible, the decantation of coarser particles of the sample.

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

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

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

9. Procedure B—Washing Using a Wetting Agent

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

9.2 After drying and determining the mass, place the test sample in the container. Add sufficient water to cover the sample, and add wetting agent to the water (Note 4). 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 solids over the nested sieves, arranged with the coarser sieve on top. Take care to avoid, as much as feasible, the decantation of coarser particles of the sample.

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

9.3 Add a second charge of water (without wetting agent) to the sample in the container, agitate, and decant as before. 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-µm (No. 200) sieve by washing as follows:

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

where:

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

11.2 Include a statement as to which procedure was used.

12. Precision and Bias

12.1 The estimates of precision of this test method listed in Table 1 are based on results from the AASHTO Materials Reference Laboratory Reference Sample Program, with testing conducted by this test method and AASHTO Method

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 time the data were acquired is that Method T 11 required, and 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.

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[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.

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APPENDIX D

ASTM METHOD FOR THE LOS ANGELES ABRASION TEST

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.

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 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[3]

D 75 Practice for Sampling Aggregates[2]

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

3. Summary of 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.

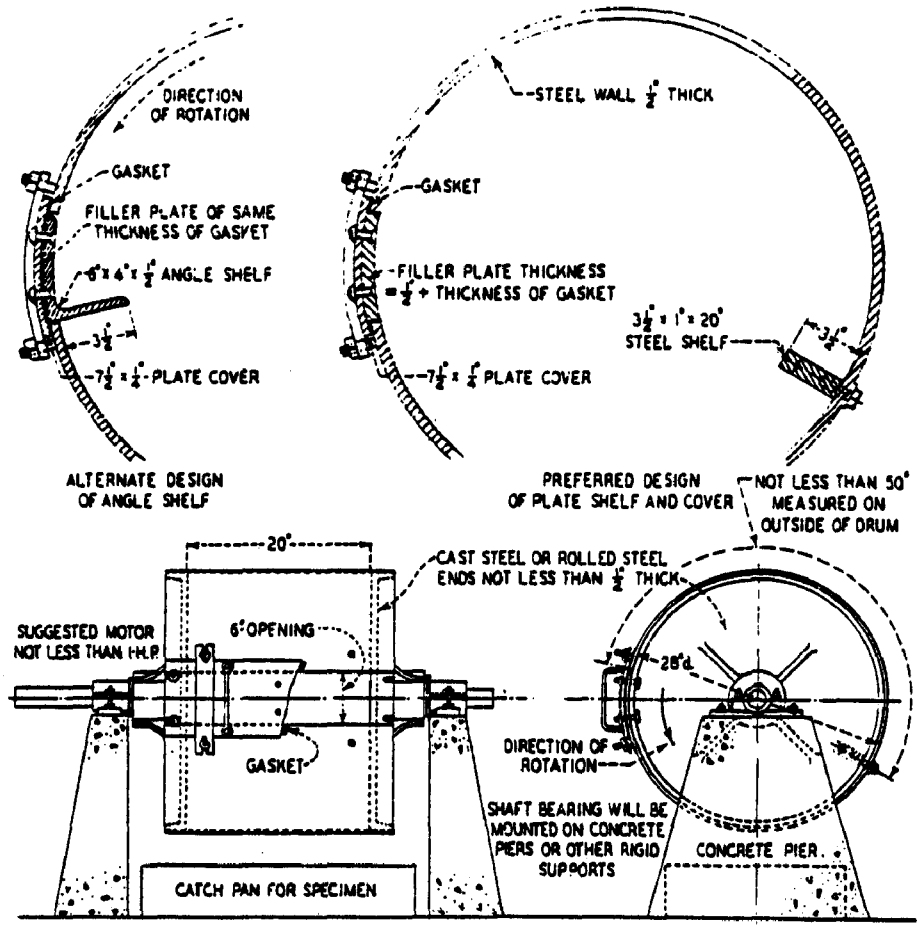
[1] This test method is under the jurisdiction of ASTM Committee C-9 on Concrete and Concrete Aggregates and is the direct responsibility of Subcommittee C09.03.05 on Methods of Testing and Specifications for Physical Characteristics of Concrete Aggregates.

Current edition approved April 24, 1981. Published June 1981. Originally published as C 131 - 37 T. Last previous edition C 131 - 76.

[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.



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 %.[5] 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 %[5] of their average. The single-operator coefficient of variation has been found to be 2.0 %.[5] 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.[5]

[5] These numbers represent, respectively, the (1S%) and (D2S%) limits as described in Practice C 670.

APPENDIX E

STATE DERIVED AGGREGATE DURABILITY TESTS

The following pages contain state-derived durability tests for construction aggregates based on AASHTO Method T-210 and ASTM Method D 3744. Test methods derived by Washington, Maine, 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)

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15. SUPPLEMENTARY NOTES

16. ABSTRACT

The purpose of this document is to identify and quantify those physical properties that can be used to select clean, durable antiskid materials (salt and sand). Test methods used to quantify the physical properties are either included or identified in this document.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Antiskid material	Roads		
Control techniques	Salt		
Fugitive dust	Sand		
Ice	Snow		
Physical properties	Test methods		
PM_{10}			
Removal techniques			

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