# FINAL REPORT FOR
# SAMPLING AND ANALYSIS PROJECT—
# BENEFICIAL USE OF RED AND BROWN MUD AND PHOSPHOGYPSUM AS ALTERNATIVE CONSTRUCTION MATERIALS

## REGIONAL APPLIED RESEARCH EFFORT (RARE) PROJECT


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# DISCLAIMER

# FOREWORD

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This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

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# 1. PROJECT DESCRIPTION AND ORGANIZATION

## 1.1 GENERAL OVERVIEW

This final report has been prepared specifically for the Regional Applied Research Effort (RARE) Project—*Beneficial Use of Red and Brown Mud and Phosphogypsum as Alternate Construction Materials*. This project was funded by the U.S. Environmental Protection Agency (EPA) Office of Research and Development. The project was performed in cooperation with EPA Region 6.

For EPA QA purposes, this project was categorized as a Sampling and Analysis project. According to MSE's Quality Management Manual's (Ref. 1) quality level definitions, this project was considered Quality Level C.

## 1.2 BACKGROUND

Red and brown muds are the secondary materials generated from the extraction of alumina from bauxite, an aluminum-containing sedimentary rock (Ref. 2). Phosphogypsum is the secondary material generated by the phosphorous fertilizer industry from phosphate-containing sedimentary rock (Ref. 3). These materials were directly discharged to water bodies until the mid-1970's. Since then, the materials have been managed in land-based units, either in surface impoundments or as mono-fill landfills. Currently, there are hundreds of millions of cubic yards of these materials located within the state of Louisiana along the Mississippi River, and the individual materials are generated annually at a rate of approximately 3 million cubic yards.

Red and brown mud and phosphogypsum, either as individual materials or as a mixture, should be considered as potential alternate construction materials, possibly in levees and/or levee support systems along the Gulf Coast. The availability of suitable construction material in southern Louisiana is limited, and the United States Army Corps of Engineers (USACE) is currently seeking 100 million cubic yards of clay material to complete construction of hurricane protection levees and floodwalls in southern Louisiana.

The projected environmental benefit and cost savings of the beneficial use of these secondary materials could be considerable. An appropriate level of assurance in the environmental performance and system design, however, is crucial in order for the proposed use of these secondary materials to be successful.

## 1.3 PREVIOUS STUDIES

In a preliminary geotechnical evaluation funded by EPA Region 6, it was demonstrated that various mixtures of these materials do exhibit characteristics of construction materials, as set forth by the USACE. Additional geotechnical evaluations, however, were performed in this study to determine if these materials (either individually or as mixtures) meet specified physical and engineering requirements, as set forth by the USACE.

## 1.4 STATEMENT OF PROJECT OBJECTIVES

The objectives of this study outlined in the Statement of Work included:

- **Task 1**—Create several "soils" by mixing red and brown mud with phosphogypsum to create a CH (fat clay) or CL (lean clay) classified material, in accordance with ASTM D2487 and the Unified Soil Classification System, with a Plasticity Index (PI) greater than 10.

- **Task 2**—Test the created "soils" (no more than three due to budgetary constraints) that meet the criteria identified under task one for specific physical and engineering parameters to determine if they meet criteria set forth in USACE EM 1110-2-1906 (laboratory soil testing procedures) (Ref. 4), relevant ASTM standards (Ref. 5 thru Ref. 14), and USACE EM 1110-2-1902 (Ref. 15) (applicability of the various shear strength tests in stability analyses).

## 2. MATERIAL DESCRIPTIONS/INITIAL CHARACTERIZATION

U.S. EPA Region 6 arranged for the sampling and shipment of the following four materials to MSE for testing:

- Fresh red/brown mud;
- Aged red/brown mud;
- Fresh phosphogypsum; and
- Aged phosphogypsum.

Each solid sample that was collected was assigned a unique sample identification (ID) number to distinguish it from all other samples. All samples were contained in 5-gallon buckets. Fresh red mud containers were labeled RMF1 to RMF5, and aged red mud containers were labeled RMA1 to RMA5 upon receipt. Fresh phosphogypsum containers were labeled PGF1 to PGF10, and aged phosphogypsum containers were labeled PGA1 to PGA10 upon receipt.

The materials were assumed to be homogeneous based on the intense processing that the materials have undergone, and all samples appeared to be homogeneous upon receipt. However, to ensure homogeneity, each container was rolled on the floor from approximately 1 minute prior to opening and inspection. Subsamples from the containers were then collected for initial characterization. Figure 2-1 shows photographs of each material (a) aged red mud, (b) fresh red mud, (c) aged phosphogypsum, and (d) fresh phosphogypsum.

Fresh red mud had visibly more moisture than aged red mud, and was reddish-brown in color, while the aged red mud was darker red to maroon in color. Both the fresh and aged phosphogypsum appeared very similar in moisture and consistency, although the aged phosphogypsum was light-gray in color, while fresh phosphogypsum was light brown in color.

Prior to beginning the materials testing, all red mud and phosphogypsum samples were screened for radiation using a calibrated Ludlum 14C Geiger Counter. Measurements were taken 30 cm from the surface of the containers with the Geiger counter readings on a 1x scale. All samples measured $\leq 0.05 \mu R/hr$. This allayed concerns about radiation exposure given the brief nature of the project. Many background reading of pavement, landscape materials, etc. had similar and higher readings than the red mud and phosphogypsum samples.


***Figure 2-1. (a) aged red mud (top left), (b) fresh red mud (top right), (c) aged phosphogypsum (bottom left), (d) fresh phosphogypsum (bottom right)***

A series of preliminary tests were performed on each of the as-received materials for initial characterization. The materials were not mechanically dried or hydrated prior to preliminary testing unless specifically required by an analysis method. The preliminary test results on as received materials are summarized in Table 2-1 below.

***Table 2-1. Summary of data collected on as received materials.***

| Material | USCS Classification (ASTM D2487) | Average Moisture Content (%) (ASTM D2216) | Minus #200 Sieve Analysis (ASTM D422) | Plasticity Index (ASTM D4318) | In Situ Shear Strength ($lb/ft^2$) (Torvane shear testing device) | Unconfined Compressive Strength ($lb/ft^2$) (Pocket penetrometer) |
|---|---|---|---|---|---|---|
| Fresh Red Mud | CL | 86.5%±1.7 (n=5) | 91.9 | 12 | 205 ±19 (n=5) | <500 |
| Aged Red Mud | CL | 25.9%±2.8 (n=5) | 75.3 | 15 | *see note | <500 |
| Fresh Phosphogypsum | ML | 35.6%±1.0 (n=10) | Not analyzed | No plasticity (NP) | *see note | *see note |
| Aged Phosphogypsum | ML | 31.4%±1.1 (n=10) | Not analyzed | 2 | *see note | *see note |
| *Note: tests were not completed due to consistency of samples | | | | | | |

The red mud materials are classified as CL or lean clays according to the Unified Soil Classification System (USCS), while the phosphogypsum samples are classified as ML or low plasticity silt. This meets one of the criteria established by USACE for construction materials for embankments and levees.

The moisture content of the samples indicated that fresh materials had higher moisture contents than their aged counterparts. Fresh red mud had the highest moisture content at 86.5%.

The material with the highest plasticity index was aged red mud at 15, while the fresh red mud had a PI of 12. Both phosphogypsum materials exhibited little or no plasticity. Dry red mud did fizz when mixed with sodium hexametaphosphate solution (a reagent used during PI determinations) and the PI determinations were difficult because the material dried out quickly. Fresh phosphogypsum was thixotropic and turned to a liquid state when tapped during the liquid limit test. Aged phosphogypsum was only moderately thixotropic.

Quick assessments of shear and compressive strength were also planned for all materials, but the consistency of aged red mud and aged and fresh phosphogypsum would not allow the tests to be performed. Shear tests on fresh red mud yielded an average in situ shear strength of 205 $lb/ft^2$. Unconfined compressive strength was determined on five samples of both red mud materials using a pocket penetrometer, and both results were $<500$ $lb/ft^2$.

The preliminary results were encouraging because the red mud materials did have PIs≥10 and were classified as CL or lean clays, thus meeting some of the USACE criteria for embankment and/or levee construction material.

# 3. RESULTS OF ADDITIONAL TESTING

After initial characterization, the project focused on testing the properties of the red mud and phosphogypsum materials when mixed together in various ratios. A general factorial design was devised to determine which mixtures would meet or exceed criteria of PI≥10. Variable factors, the number of levels for each variable, and the level descriptions for the Stat-Ease® experimental design for this experiment are summarized in Table 3-1.

***Table 3-1. Variable factors, levels, and level descriptions for experimental design.***

| Factor | Number of Levels | Level Description |
|---|---|---|
| Red Mud Age | 2 | Fresh or Aged |
| Red Mud Weight Ratio | 4 | 1,2, 3, or 4 |
| Phosphogypsum Weight Ratio | 2 | 1 or 2 |
| Phosphogypsum Age | 2 | Fresh or Aged |

The critical response variable was the PI of each prepared mixture.

From previous work, it was known that phosphogypsum has little to no plasticity, so it was expected that a higher ratio of red mud to a lower ratio of phosphogypsum would be more likely to meet the initial criteria of PI ≥ 10. Previous work using volumetric ratios of red mud: phosphogypsum of 1:1, 2:1, and 1:2 did not yield a PI ≥ 10 (Ref. 16), so it was surmised that more red mud would be needed to achieve a PI ≥ 10.

Stat-Ease Design Expert® (version 7.1.5) was used to generate a general factorial design with 2 levels of red mud age, 4 levels of red mud weight ratios, 2 levels of phosphogypsum weight ratios, and 2 levels of phosphogypsum age. This factorial design therefore has a treatment structure of 2x4x2x2, with a completely randomized design structure. Mixing speed and mixing time were held constant for all mixtures.

## 3.1 PLASTICITY INDEX SCREENING RESULTS

Samples for plasticity index determinations were prepared by placing 200 grams of each mixture (with appropriates ratios of red mud and phosphogypsum) in a mixing bowl. The materials were then mixed with a dual-paddle mixer for 30 seconds, placed in a Ziploc bag, and kneaded by hand for one minute. Subsamples were then collected for moisture content and plasticity index determinations. Table 3-2 summarizes the plasticity index and moisture content results from the initial mixtures. Samples with PI≥10 are highlighted.

*Table 3-2. PI and moisture content results from general factorial experiments.*

| Run Order | Factor 1: Age red mud | Factor 2: Weight Ratio red mud | Factor 3: Weight Ratio phospho-gypsum | Factor 4: Age phospho-gypsum | Response 1: Plasticity Index (ASTM D4318) | Moisture Content (%) (ASTM D2216) | Comments |
|---|---|---|---|---|---|---|---|
| 1 | Fresh | 2 | 1 | Fresh | 20 J | 63.5 | |
| 2 | Aged | 3 | 2 | Fresh | NP | 22.5 | |
| 3 | Aged | 4 | 1 | Fresh | 16 | 70.6 | |
| 4 | Aged | 1 | 2 | Aged | 1 | 29.2 | |
| 5 | Aged | 3 | 1 | Aged | 11 | 23.1 | |
| 6 | Aged | 2 | 2 | Aged | 5 | 27.1 | 1:1 replicate of run #24 |
| 7 | Fresh | 2 | 1 | Aged | 25 J | 61.0 | |
| 8 | Fresh | 1 | 2 | Fresh | NP | 42.4 | |
| 9 | Fresh | 1 | 1 | Aged | 20 | 51.7 | |
| 10 | Fresh | 4 | 2 | Aged | 14J | 61.4 | 2:1 replicate of run #7 |
| 11 | Aged | 2 | 2 | Fresh | NP J | 28.5 | 1:1 replicate of run #31 |
| 12 | Fresh | 2 | 2 | Aged | 19 | 51.5 | 1:1 replicate of run #9 |
| 13 | Aged | 4 | 2 | Aged | Not analyzed | Not analyzed | 2:1 replicate of run #29 |
| 14 | Aged | 3 | 2 | Aged | 7 | 27.2 | |
| 15 | Fresh | 3 | 2 | Fresh | 5 | 56.0 | |
| 16 | Aged | 3 | 1 | Fresh | 4 | 26.7 | |
| 17 | Aged | 4 | 1 | Aged | 17 | 24.5 | |
| 18 | Fresh | 3 | 1 | Fresh | 7 | 69.6 | |
| 19 | Fresh | 3 | 1 | Aged | 23 | 65.4 | |
| 20 | Fresh | 2 | 2 | Fresh | 7 | 53.5 | 1:1 replicate of run #23 |
| 21 | Fresh | 1 | 2 | Aged | 11 | 44.7 | |
| 22 | Fresh | 4 | 1 | Fresh | Not analyzed | Not analyzed | |
| 23 | Fresh | 1 | 1 | Fresh | 5 | 57.6 | |
| 24 | Aged | 1 | 1 | Aged | 3 | 26.3 | |
| 25 | Aged | 1 | 2 | Fresh | NP | 31.3 | |
| 26 | Fresh | 4 | 1 | Aged | 2 | 26.4 | |
| 27 | Fresh | 3 | 2 | Aged | 14 | 50.2 | |
| 28 | Fresh | 4 | 2 | Fresh | 2 J | 66.9 | 2:1 replicate of run #1 |
| 29 | Aged | 2 | 1 | Aged | 5 | 24.4 | |
| 30 | Aged | 4 | 2 | Fresh | NP | 28.3 | 2:1 replicate of run #32 |
| 31 | Aged | 1 | 1 | Fresh | 4 J | 27.1 | |
| 32 | Aged | 2 | 1 | Fresh | 2 | 27.5 | |

"J" flag indicates that the associated value is estimated.
"NP" indicates no plasticity.

## 3.2 STATISTICAL ANALYSIS OF THE PI DATA SET

Stat-Ease Design Expert® (version 7.1.5) was used to: analyze the PI data to determine which factors were significant; assess the interactions between factors; optimize the statistical model; and determine the best mixtures based on the results of the tests. The results of this analysis determined the significant variables and the interactions among variables.

Two tests #13 (2PGA:4RMA) and #22 (1PGF:4RMF) were not performed, so these rows were ignored by Stat-ease. Based on the results given in the effects list generated by Stat-ease, model terms selected included A (age red mud), B (weight ratio red mud), C (weight ratio phosphogypsum, D (age phosphogypsum), AB (interaction between factors A and B), AD (interaction between A and D), and ABC (interactions between A, B, and C). Table 3-3 summarizes the effects list below with the selected model terms highlighted.

***Table 3-3. Effects list output from Stat-ease.***

| Model Term | Degrees of Freedom | Sum of Squares | Mean Square | % Contribution |
|---|---|---|---|---|
| A—age red mud | 1 | 326.7 | 326.7 | 18.9 |
| B—weight ratio red mud | 3 | 100.05 | 33.35 | 5.79 |
| C—weight ratio phosphogypsum | 1 | 245.34 | 245.34 | 14.2 |
| D—age phosphogypsum | 1 | 286.62 | 286.62 | 16.6 |
| AB | 3 | 356.40 | 118.8 | 20.6 |
| AC | 1 | 0.14 | 0.14 | 0.008 |
| AD | 1 | 61.16 | 61.16 | 3.54 |
| BC | 3 | 12.59 | 4.20 | 0.728 |
| BD | 3 | 16.11 | 5.37 | 0.932 |
| CD | 1 | 0.30 | 0.30 | 0.017 |
| ABC | 3 | 268.74 | 89.58 | 15.6 |
| ABD | 3 | 23.67 | 7.89 | 1.37 |
| ACD | 1 | 2.67 | 2.67 | 0.154 |
| BCD | 2 | 16.75 | 8.38 | 0.969 |
| ABCD | 2 | 11.08 | 5.54 | 0.641 |

With these model terms selected, an analysis of variance (ANOVA) was performed. The results from the ANOVA are presented in Table 3-4 below.

***Table 3-4. ANOVA (classical sum of squares—Type III) for selected factorial model.***

| Source | Sum of Squares | df | Mean Square | F Value | Prob > F | p-value |
|---|---|---|---|---|---|---|
| Model | 1657.73 | 17 | 97.51 | 16.58 | < 0.0001 | significant |
| *A-Age Red Mud* | *319.20* | *1* | *319.20* | *54.28* | *< 0.0001* | |
| *B-Weight Ratio RM* | *100.17* | *3* | *33.39* | *5.68* | *0.0117* | |
| *C-Weight Ratio PG* | *140.80* | *1* | *140.80* | *23.94* | *0.0004* | |
| *D-Age PG* | *378.89* | *1* | *378.89* | *64.43* | *< 0.0001* | |
| *AB* | *366.14* | *3* | *122.05* | *20.75* | *< 0.0001* | |
| *AC* | *1.16* | *1* | *1.16* | *0.20* | *0.6644* | |
| *AD* | *116.04* | *1* | *116.04* | *19.73* | *0.0008* | |
| *BC* | *12.59* | *3* | *4.20* | *0.71* | *0.5624* | |

| Source | Sum of Squares | df | Mean Square | F Value | Prob > F | p-value |
|---|---|---|---|---|---|---|
| *ABC* | *268.74* | *3* | *89.58* | *15.23* | *0.0002* | |
| Residual | 70.57 | 12 | 5.88 | | | |
| Cor Total | 1728.30 | 29 | | | | |
| Standard Deviation | 2.43 | | R-squared | 0.9592 | | |
| Mean | 8.3 | | Adjusted R-squared | 0.9013 | | |
| C.V.% | 29.22 | | Adequate Precision | 15.63 | | |

The Model F-value of 16.58 implies the model is significant. There is only a 0.01% chance that a Model F-Value this large could occur due to noise. Values of Prob > F less than 0.0500 indicate model terms are significant. In this case A, B, C, D, AB, AD, ABC are significant model terms. The Adequate Precision, which measures the signal to noise ratio (a ratio greater than 4 is desirable), of 15.63 indicates an adequate signal.

Figure 3-1 Below shows the normal probability plot of studentized residuals and indicated the normality of the residuals.

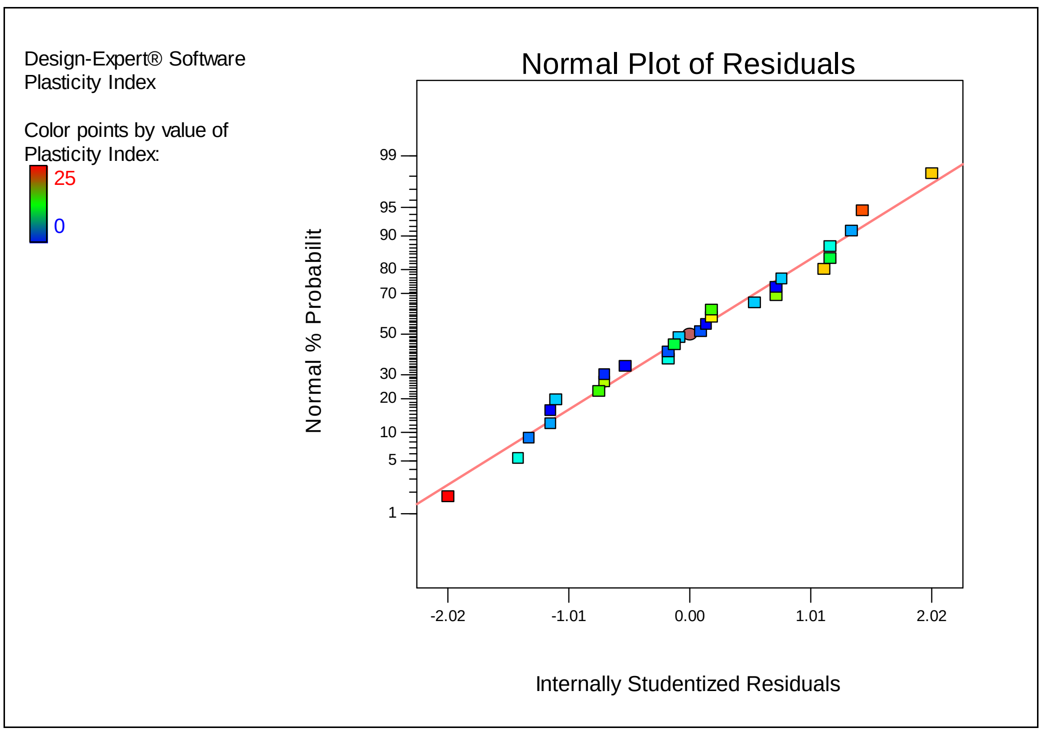


***Figure 3-1. Normal plot of residuals.***

Figure 3-2 below shows the externally studentized range and all values are with in the appropriate range, indicating no outliers.

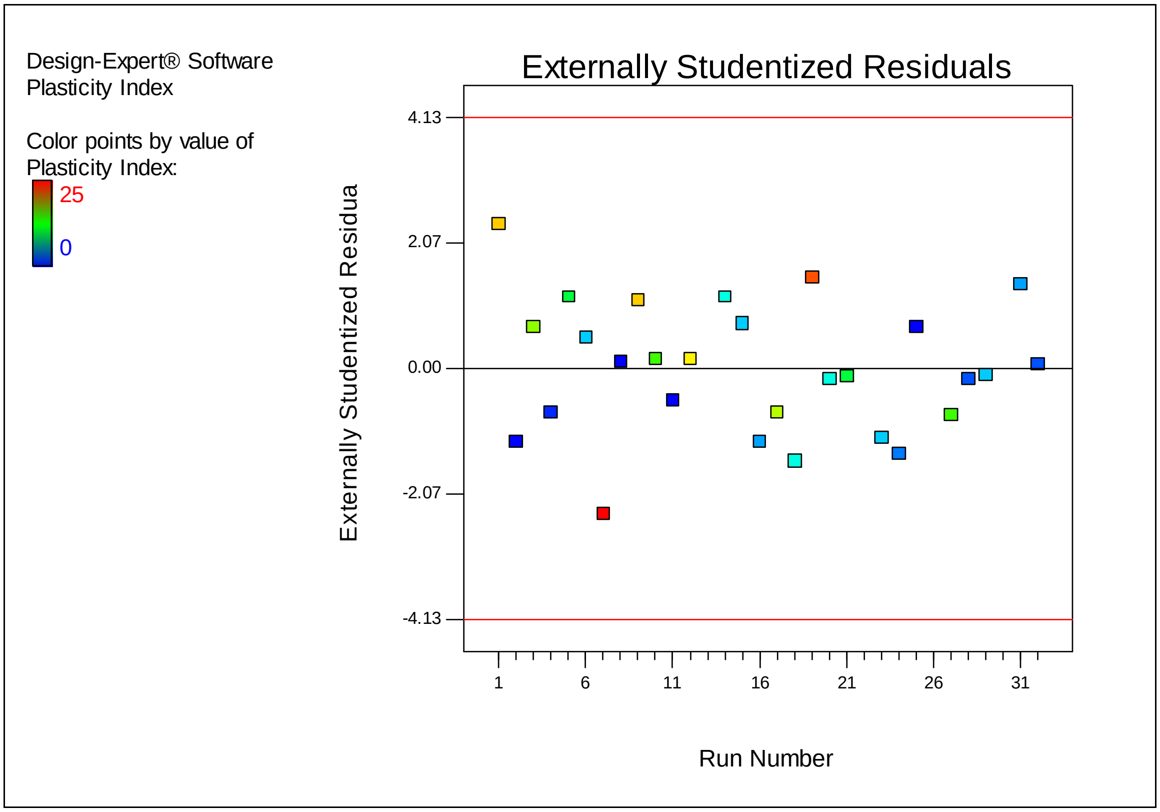


***Figure 3-2. Externally studentized residuals.***

After determining that the model was valid, the project team narrowed acceptable results to include mixture ratios that would result in a PI between 10 and 20. Mixtures with values above 20, were considered to have undesirable characteristics that would be difficult to apply in the field without the development of specialized handling, placement, and compaction procedures. There were eight model-generated solutions identified by Stat-ease as presented in Table 3-5. Please note that the PI values are those predicted by the model constructed from experimental data.

***Table 3-5. Solutions for 32 combinations of categoric factor levelsfor PI range 10 to 20.***

| Solution Number | Age red mud | Weight ratio red mud | Age phosphogypsum | Weight ratio phosphpgypsum | PI Values predicted by Model | Desirability | Comments |
|---|---|---|---|---|---|---|---|
| 1 | Fresh | 4 | Aged | 2 | 13.7 | 1.0 | |
| 2 | Fresh | 1 | Aged | 1 | 18.2 | 1.0 | Selected based on equal ratios which would be easy to implement in the field. |
| 3 | Aged | 4 | Fresh | 1 | 14.9 | 1.0 | |
| 4 | Fresh | 2 | Fresh | 1 | 16.8 | 1.0 | |
| 5 | Aged | 4 | Aged | 1 | 18.1 | 1.0 | Selected based on material consistency and both aged materials which |

| Solution Number | Age red mud | Weight ratio red mud | Age phosphogypsum | Weight ratio phosphpgypsum | PI Values predicted by Model | Desirability | Comments |
|---|---|---|---|---|---|---|---|
| | | | | | | | means availability of large quantities. |
| 6 | Fresh | 1 | Aged | 2 | 11.2 | 1.0 | |
| 7 | Fresh | 2 | Aged | 2 | 18.7 | 1.0 | Replicate of solution #2 |
| 8 | Fresh | 3 | Aged | 2 | 15.2 | 1.0 | Selected based to determine how additional fresh red mud would influenc geotechnical performance when compared to 1RMF:1PGA |

Fresh red mud was a key ingredient to making a mixture in the PI range of 10 to 20, and 6 of the 8 mixtures used fresh red mud. This was probably due to the moisture, which bonded to the phosphogypsum to create a plastic mixture; however the extra moisture was also a hindrance to mixtures containing fresh red mud because it made the mixtures sticky and probably not ideal for use in construction of levees or embankments. In fact, additional red mud whether fresh or aged resulted in higher PI values as the weight ratio was increased except when fresh red mud was at weight ratio 4. The high moisture content of fresh red mud was probably the reason for this when used in samples with only 1 part phosphogypsum to 4 parts fresh red mud. Aged red mud in higher ratios yielded higher PI values. This is illustrated by Figure 3-3, which displays the interaction between weight ratio and the age of the red mud (with phosphogypsum aged at weight ratio 1).

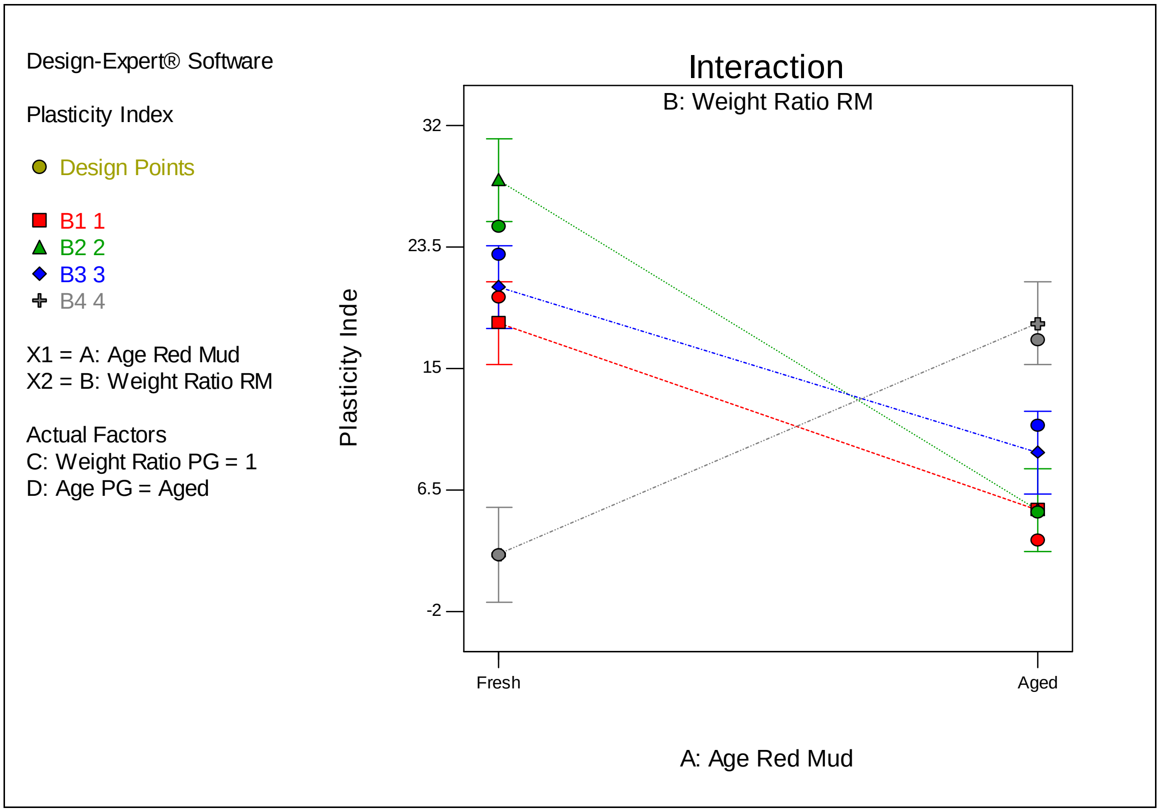


***Figure 3-3. Interaction between weight ratio and the age of the red mud.***

### 3.3 SELECTION OF MIXTURES FOR FURTHER TESTING

EPA set the requirement that only materials with PI ≥ 10 would be considered for further testing based on input from USACE. Eleven of the 32 mixtures did have PI's greater than 10. These values are highlighted in Table 3-2 above. The statistical model indicated 8 solutions with PI values between 10 and 20.

In addition to PI, a qualitative measurement of reactivity between the two materials (i.e. temperature, color, effervescence, shrink/swell, etc.) was considered as another distinguishing factor; however there was never an indication of a reaction between the two materials when mixed in any of the ratios. Of the 11 mixtures meeting the PI criteria and the 8 solutions provided by Stat-ease, only 3 could be selected for further consideration because many of the mixtures appeared to be of wet consistency not suitable for embankment or levee construction without development and implementation of special placement and compaction procedures.

Based on the statistical analysis, the PI results, and other qualitative factors (usability in the field, consistency, moisture content, etc.). The three mixtures selected for further testing included:

1) 1 part phosphogypsum aged to 1 part red mud fresh (1PGA:1RMF);
2) 2 parts phosphogypsum aged to 3 parts red mud fresh (2PGA:3RMF); and
3) 1 part phosphogypsum aged to 4 parts red mud aged (1PGA:4RMA).

## 3.4 RESULTS OF FURTHER TESTING

Large batches (175lb) of the three preferred ratios listed above were mixed for additional testing. After adding the appropriate amounts of each material in a 55-gallon drum, a dual paddle mixer was used to mix the samples for 30 seconds. The mixture was then rolled in the drum for an additional 30 seconds, mixed with the paddle mixer for an additional 30 seconds, then placed on plywood and kneaded by hand for 5 minutes. The mixtures were then stored in sealed 5-gallon containers to await testing.

With further handling of larger quantities of these preferred mixtures, the 1PGA:1RMF and 2PGA:3RMF mixtures had excessively high moisture contents and high shrinkage potential upon drying. This was confirmed by performing shrinkage and unconfined compressive strength testing on samples of the 1PGA:1RMF mixtures. The UCS testing was performed at EPA's direction to determine if drying of the samples would increase their strength. Tests after drying were performed for 1PGA:1RMF and aged red mud alone. The results of this testing indicated a 22.7% shrinkage and excessive cracking of the 1PGA:1RMF samples upon drying for 96 hours. It was assumed that the 2PGA:3RMF mixture would have a higher shrinkage potential and a higher susceptibility to cracking due to its higher water content than 1PGA:1RMF. Only approximately 5.5% shrinkage was observed in the aged red mud sample, with all of the shrinkage occurring in the first 24 hours. Drying of the aged red mud for 96 hours decreased the strength of the sample by approximately 40%, while drying of the 1PGA: 1RMF sample for the same amount of time increased its strength by over 500%. The results of these shrinkage and UCS tests on the 1PGA:1RMF and aged red mud samples are presented in Table 3-6 below. Details of the tests can be found in Appendix A.

***Table 3-6. Results of UCS/Shrinkage drying tests for 1PGA:1RMF and aged red mud.***

| Sample ID | Unconfined Compressive Strength (kPa) | Total Shrinkage (%) | Comments |
|---|---|---|---|
| 1PGA:1RMF (1B) (dried 24 hours) | 103.9 | 11.0 | While drying increased strength, cracks were visible in sample |
| 1PGA:1RMF (1C) (dried 96 hours) | 689.4 | 22.7 | Further drying again increased strength, but visible cracks were noted in sample |
| Aged red mud (4A) (dried for 24 hours) | 507.8 | 5.5 | No apparent cracks visible |
| Aged red mud (4B) (dried for 96 hours) | 358.1 | 5.5 | Drying sample decreased strength |

Based on the high moisture content and high shrinkage potential of the 1PGA:1RMF material, it is MSE's opinion that the 1PGA:1RMF and 2PGA:3RMF would not make suitable construction materials without development of appropriate quality control, special placement, and compaction procedures. Because these mixtures did not appear to be applicable to the goals of the project, all further analysis on these materials was suspended and further work focused on aged red mud alone and the mixture of 1PGA:4RMA.

### 3.4.1 "Soil" Classification

The USCS was used in accordance with ASTM D2487 to classify the three preferred mixtures based on their Liquid Limit, Plastic Limit (ASTM D2434), and minus #200 sieve analyses (ASTM D422) in various ratios. The results are summarized in Table 3-7 below.

***Table 3-7. Soil classification of selected mixtures.***

| Sample ID | Soil Classification | Visual Observations |
|---|---|---|
| 1PGA:4RMA | CL | Fine silty clay with some rock fragments, moist, dark red/maroon with gray speckles |
| 1PGA:1RMF | CL | Fine silty clay, wet, reddish/brown |
| 2PGA:3RMF | CL | Fine silty clay with some rock fragments, wet, dark red/maroon |

### 3.4.2 Standard Proctor

Standard Proctor testing (in accordance with ASTM D698) was performed on the 3 preferred mixtures and the aged red mud. Moisture-density curves for each material are contained in Appendix B. The results are summarized in Table 3-8 below.

***Table 3-8. Standard Proctor test results of selected mixtures.***

| Sample ID | Optimum Water Content (%) | Maximum Dry Density ($lb/ft^3$) |
|---|---|---|
| 1PGA:1RMF | 30.4 | 92.2 |
| 1PGA:4RMA | 32.4 | 97.9 |
| 2PGA:3RMF | 32.9 | 93.0 |
| Aged Red Mud | 32.2 | 100.2 |

As shown by the results above, the maximum dry densities ranged from 92.2 to 100.2 $lb/ft^3$ with aged red exhibiting the highest maximum dry density. Optimum water contents for the materials tested were in a range between 30.4 to 32.2%.

### 3.4.3 Saturated Paste pH

The saturated paste pH of the selected optimum mixture (1PGA:4RMA) and aged red mud was determined according to *Methods of Soil Analysis,* ASA Method 10 2.3.1/10 3.2. The saturated paste pH values are summarized in Table 3-9 below.

***Table 3-9. Saturated paste pH results for selected materials.***

| Sample ID | Saturated Paste pH |
|---|---|
| 1PGA:4PGA | 7.4 |
| Aged Red Mud | 8.6 |

The saturated paste pH values indicate that aged red mud has moderately alkaline pH, and the 1PGA:4PGA mixture is near neutral.

### 3.4.4 Consolidation/Swell

A 1-dimensional consolidation/swell test in accordance with ASTM D2435 was performed on the 1PGA:4RMA mixture and can be found in Appendix C. An undisturbed sample of this material was collected by driving the consolidation-swell loading ring through a 1PGA:4RMA sample that was compacted to approximately 90% of maximum dry density at near optimum moisture content. The sample was inundated with water at the beginning of the test and remained submerged in water throughout the remainder of the test. The results, which are presented in Appendix B indicate a Compression Index (Cc) of approximately 0.136 and a Recompression Index (Cr) of approximately 0.013. The coefficient of consolidation (Cv) was computed for each increment of load and are presented with the consolidation curve. The preconsolidation pressure ($\sigma_p$) was determined to be approximately 150 kPa using the Casagrande method. Due to the relatively large $\sigma_p$, it is presumed that this particular soil will be overconsolidated under most loading conditions while in place in a typical embankment or levee system.

### 3.4.5 Triaxial Shear Strength/Permeability

Samples for shear strength were compacted to approximately 90% of maximum dry density at near optimum moisture content in three lifts with each lift being scarified to encourage bonding between lifts. The samples were not allowed to dry prior to testing. Samples were subjected to two separate confining pressures and compressed at a strain rate of approximately 1% per minute. Stress-strain curves for each sample are presented in Appendices D (Q-tests) and E (R-tests). Tables 3-10 and 3-11 summarize the results for unconsolidated-undrained triaxial compression tests (Q-test) according to ASTM D2850-03a and consolidated-drained triaxial compression tests (R-test) according to ASTM D4767, respectively.

***Table 3-10. Unconsolidated-Undrained "Q-Test" Triaxial Shear Strength results for selected materials.***

| Sample ID | Total Confining Stress (kPa) | Compressive Strength (kPa) | Major Principal Total Stress (kPa) | Comments |
|---|---|---|---|---|
| 1PGA:4RMA (3A) | 13.9 | 12.1 | 26.0 | None |
| 1PGA:4RMA (3B) | 34.3 | 22.8 | 57.2 | No true failure planes observed |

***Table 3-11. Consolidated-Undrained "R-Test" Triaxial Shear Strength results for selected materials.***

| Sample ID | Effective Minor Principal Stress (kPa) | Effective Major Principal Stress (kPa) | Deviator Stress (kPa) |
|---|---|---|---|
| 1PGA:4RMA (3F-4) | 165.0 | 417.5 | 252.6 |

As shown above and in the detailed results in Appendix B, sample 3B from the UU testing did not shear diagonally through the sample, but instead broke along two of the layers prior to taking the picture. Samples 3F-1 and 3F-3 are not included in Table 3-8 and were originally setup for CU testing, but were accidentally sheared with the pore pressure valves open. The results from Samples 3F-1 and 3F-2, which were actually tested under Consolidated-Drained (CD) conditions, are presented in section 3.4.8-Direct Shear "S-Testing".

### 3.4.6 Hydraulic Conductivity

The triaxial device was also used to determine the hydraulic conductivity of 1PGA:4RMA samples according to ASTM D5084-03. The samples were compacted to approximately 90% of maximum dry density at near optimum moisture content in three lifts with each lift being scarified to encourage bonding between lifts. The hydraulic conductivity results are summarized in Table 3-12 below.

*Table 3-12. Saturated hydraulic conductivity results for selected materials*

| Sample ID | Effective Stress (KPa) | Hydraulic Conductivity (cm/sec) | Comments |
|---|---|---|---|
| 3F-1 (1PGA:4RMA) | 27.6 | $3.6x10^{-4}$ | |
| 3F-3 (1PGA:4RMA) | 41.4 | $1.8x10^{-4}$ J | Value is estimated because hydraulic conductivity values did not stabilize such that all readings were within ±25% of the mean value. A leaky membrane was suspected. |
| 3F-4 (1PGA:4RMA) | 55.2 | $5.0x10^{-5}$ | |

### 3.4.8 Direct Shear S

Direct shear testing was performed on 1PGA:4RMA samples at normal stresses of approximately 1000 lb/ft$^2$, 3000 lb/ft$^2$, and 5000 lb/ft$^2$ according to ASTM D3080. The direct shear results are summarized in Table 3-13 and in Appendix F.

*Table 3-13. Direct shear testing results for selected materials.*

| Sample ID | Cohesion (c) | Friction Angle (phi) |
|---|---|---|
| 1PGA:4RMA | 2775 | 69° |

As described in section 3.4.5 above, Samples 3F-1 and 3F-3, which were originally to be tested under CU conditions, but were accidentally sheared under CD conditions, are presented in Table 3-14 below and in Appendix F.

*Table 3-14. Consolidated-Drained Triaxial Shear Strength results for selected materials.*

| Sample ID | Effective Minor Principal Stress (kPa) | Effective Major Principal Stress (kPa) | Deviator Stress (kPa) | Comments |
|---|---|---|---|---|
| 1PGA:4RMA (3F-1) | 264.5 | 598.8 | 334.3 | Pore pressures allowed to dissipate during shearing |
| 1PGA:4RMA (3F-3) | 414.2 | 695.5 | 281.3 | Pore pressures allowed to dissipate during shearing |

The results displayed in Table 3-11 above can be used to obtain an estimate of the shear strength parameters c and phi when plotted.

In addition to the Geotechnical testing described in the sections above, MSE also prepared samples of 1PGA:4RMA and shipped them to Vanderbilt University for further leach testing/modeling to determine how these materials will behave in the environment.

# 4. QUALITY ASSURANCE ACTIVITIES

Quality assurance activities included independent data review and validation. All calibrations were verified prior to initiation of testing. A displacement transducer had to be replaced on the triaxial device prior to initiation of testing. The triaxial device for the consolidated-undrained tests malfunctioned, not allowing an automatic test, so the tests were run manually at the same strain rate.

All QC checks (duplicates) performed during the testing were within control limits except for one falling head permeability test to determine saturated hydraulic conductivity. This data point was flagged “J” to indicate that the value is estimated. This is summarized in Table 4-1 below.

Because there was replication built into the factorial design, the Atterberg limits and moisture content results were also reviewed to determine how closely these results were replicated. While moisture content percent differences were all in control indicating very good agreement (0.4 to 7.4% relative percent difference), three of the replicates for PI were not within the ±2 PI units control limit established. Sample results and replicate sample results were flagged “J” as estimated values. These results are summarized in Table 4-1 below.

***Table 4-1. Summary of QC checks.***

| Analysis | Sample (Result) | Sample Replicate (Result) | Control Limit | Result/Corrective Action |
|---|---|---|---|---|
| Falling Head Permeability (ASTM D5084) | 3F-3 (1PGA:1RMA) | N/A | 4 consecutive readings within ±25% of the mean of those 4 readings | Flag results as ”J”, estimated. |
| Atterberg Limits (ASTM D4318) | PGF1:RMF2 (20)<br>PGA1:RMF2 (25)<br>PGF1:RMA1 (4) | PGF2:RFM4 (2)<br>PGA2:RMF4 (14)<br>PGF2:RMG2 (NP) | Difference >±2 PI units | Flag results as “J”, estimated. |

## 4.1 DEVIATIONS FROM THE QAPP

The following deviations from the QAPP were implemented during the project:

- The original test design in the QAPP has 3 levels of red mud weight ratio (2,3, and 4), but a fourth level (weight ratio 1) was added to cover a wider range of red mud weight ratios.
- The ≤ 20% relative percent difference (RPD) criteria for Atterberg limits given in the QAPP was not appropriate because the result is rounded to the nearest whole number. Instead, a control limit of absolute difference of ±2 PI units was used.
- Three samples were to be selected for further testing after PI screening tests. Based on properties of some of the materials, testing was focused on a 1:PGA:4RMA mixture and aged red mud alone.
- At EPA’s direction, tests to assess the behavior of 1PGA:1RMF and red mud alone as samples air dried for 24 hours and 96 hours were added.

# 5. CONCLUSIONS/RECOMMENDATIONS

The purpose of this study was to determine the applicability of utilizing red/brown mud and phosphogypsum as construction materials when mixed in various ratios. The results of this study suggest that there is potential to utilize these materials for levee construction from a geotechnical standpoint. The following conclusions were drawn based on this testing:

- The most promising ratio identified for creating a new construction material from red mud and phosphogypsum wastes was 1PGA:4RMA.
- Fresh red mud in its natural state or as a mixture of 1PGA: 1RMF and 2PGA: 3RMF has an excessive amount of moisture and would be difficult to use as embankment or levee construction

material without the development and implementation of special placement and compaction procedures. In addition, excessive cracking was observed in the 1PGA:1RMF samples after air drying for 96 hours, indicating that this material may not be suitable for embankment, levee or other impoundment structures.
- Further consideration should be given to using aged red mud alone to provide needed construction materials. The results of testing described in this report may be used as a starting point for such additional testing.

Recommendations for further testing include:

- Studying the effect of moisture content and saturation on geotechnical properties of red mud and red mud mixed with phosphogypsum;
- Focusing testing on the aged red mud material to further optimize the ratios of red mud to phosphogypsum for this application;
- Exploring how additional additives (i.e., fly ash, polymer, etc.) might further optimize these created "soils" and result in even better potential construction materials;
- Challenging this material at pilot-scale utilizing water from the Gulf Coast region to simulate conditions that the material would be exposed to in practice; and
- Testing materials at conditions and boundaries specified by USACE to ensure applicability of results.

Recommendations for utilizing this material in the field include the following.

- Investigating/optimizing mixing and placement procedures.
- Utilizing the created "soil" as the internal construction material of the levee to avoid direct contact with the environment but provide access to needed construction materials.
- The 1PGA:4RMA preferred composite was relatively easy to handle and to mix thoroughly using dual-paddle mixers followed by kneading of the material by hand. In MSE's opinion, large-scale mixing of this material would be feasible using many conventional mechanical mixing procedures, such as larger twin-shaft rotary paddles, a pug-mill, or other equivalent and comparable methods.
- The 1PGA:4RMA preferred composite should be placed evenly and properly compacted in loose lifts not exceeding 1.0 foot in thickness during embankment construction. In order to ensure proper placement and compaction, a qualified Geotechnical Engineer and testing laboratory should be retained during initial construction to provide field density testing of compacted materials. As described in Section 1.7.5-Compaction of the Unified Facilities Guide Specifications (UFGS), dated May 2008 (Ref. 17), each layer of compacted fill shall be compacted to at least 90 percent of maximum dry density as determined by ASTM D698 at a moisture content within 5 above and 3 below the optimum moisture content. If soft or yielding areas are observed during placement or compaction, a woven geotextile fabric should be placed between successive lifts. As described in the UFGS, the first layer above the geotextile fabric should be placed and compacted by construction equipment have a ground pressure no greater than 4.7 +/- 0.2 pounds per square inch (psi).
- All other pertinent construction recommendations described in the UFGS should be followed during construction of embankments using the 1PGA:4RMA material.
- Consider the use of red mud alone to avoid the additional mixing step needed to incorporate phosphogypsum.

Further test work will be performed by Vanderbilt University to determine if the mixtures identified in this study will be compatible with the surrounding environment. Based on the results of this study, further consideration of using these materials to partially supply the needed clay material for levee and/or embankment construction is warranted.

## 6. REFERENCES


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# APPENDIX A

UCS Test Data

# Unconsolidated-Undrained Triaxial Compression Test on Cohesive (Quick Undrained)

| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | NA |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 1B |

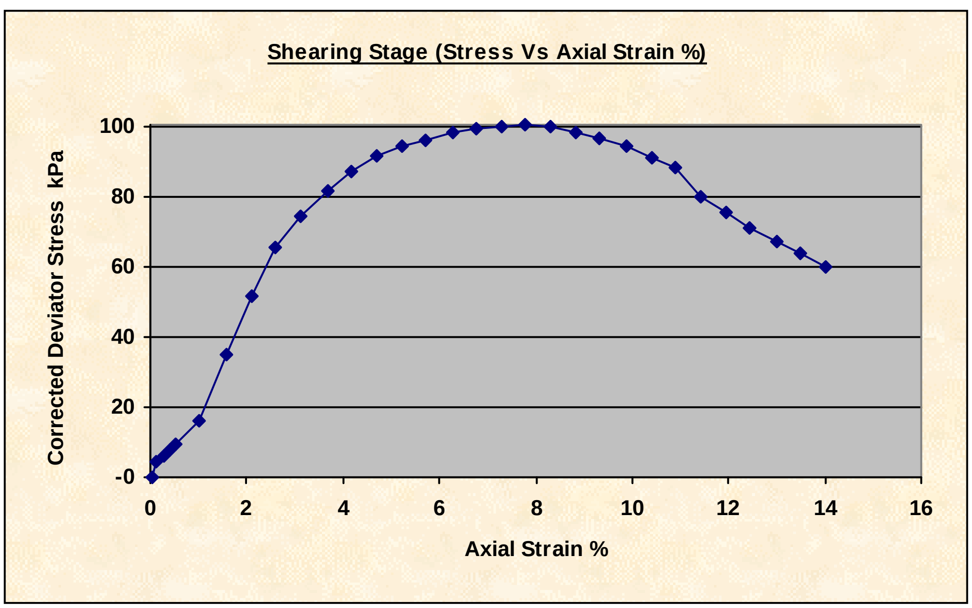
## Test & Sample Details

| | | | |
|---|---|---|---|
| **Standard** | ASTM D2850-03a | **Sample Depth** | NA |
| **Sample Type** | Small disturbed sample | **Sp. Gravity of Solids** | 2.70 |
| **Sample Description** | 1 Part PGA to 1 Part RMF compacted wet and dried 24 hours | **Lab. Temperature** | 23.0 deg.C |
| **Variations from Procedure** | No confining pressure was applied | | |

## Specimen Details

| | | | |
|---|---|---|---|
| **Specimen Reference** | B | **Stage Reference** | 1 |
| **Initial Height** | 104.56 mm | **Description** | Red Mud and Phosphogypsum Composite |
| **Initial Diameter** | 68.26 mm | **Depth within Sample** | NA |
| **Initial Dry Unit Weight** | 15.85 kN/m3 | **Orientation within Sample** | NA |
| **Initial Moisture Content*** | 32.3 % (trimmings: 31.8 %) | **Preparation** | Soil was compacted in a 3" diameter by 5.5" long mold with a rubber membrane the membrane was removed and the sample was allowed to air dry for 24 hours prior to test |
| **Void Ratio** | 0.73 | **Degree of Saturation** | 123.34% |
| **Comments** | None | | |

* Calculated from initial and dry weights of whole specimen



Unconsolidated-Undrained Triaxial Compression Test on Cohesive (Quick Undrained)

| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | NA |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 1B |

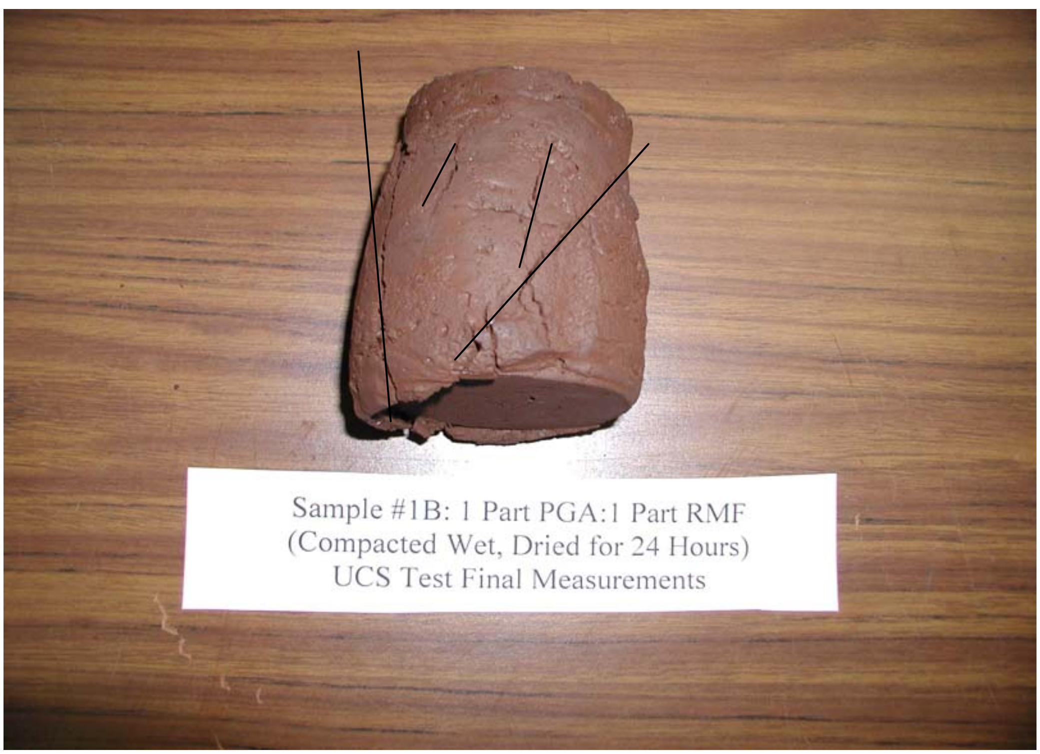
## Shear Conditions

| | | | |
|---|---|---|---|
| **Rate of Axial Strain** | 1.00%/min | **Cell Pressure** | 0.0kPa |

## Conditions at Failure

| | | | |
|---|---|---|---|
| **Failure Criterion** | Maximum Deviator Stress | | |
| **Compressive Strength** | 103.9 kPa | **Major Principal Stress ($\sigma_1$)** | 103.9 kPa |
| **Axial Strain** | 7.79% | **Minor Principal Stress ($\sigma_3$)** | 0.0 kPa |
| **Deviator Stress Correction Applied** | 0.00 kPa | **Final Moisture Content** | 31.8 % |
| **Final Unit Weight** | 20.88 kN/m3 | | |

| | |
|---|---|
| Tested By and Date: | NAJ 7/18/08 |
| Checked By and Date: | KMP 7/18/08 |
| Approved By and Date: | NAJ 8/18/08 |




Mode of Failure

# Unconsolidated-Undrained Triaxial Compression Test on Cohesive (Quick Undrained)

| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | NA |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 1C |

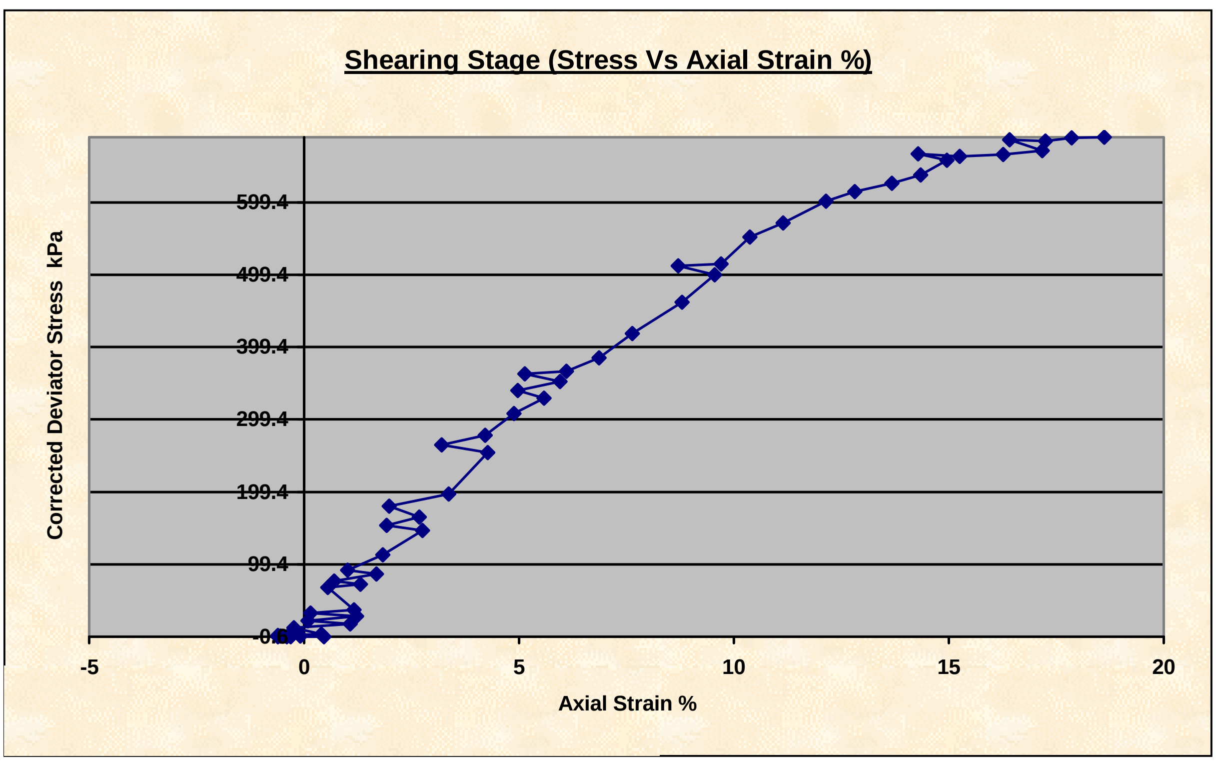
## Test & Sample Details

| | | | |
|---|---|---|---|
| **Standard** | ASTM D2850-03a | **Sample Depth** | NA |
| **Sample Type** | Small disturbed sample | **Sp. Gravity of Solids** | 2.70 |
| **Sample Description** | 1 Part PGA to 1 Part RMF compacted wet and dried 96 hours | **Lab. Temperature** | 23.0 deg.C |
| **Variations from Procedure** | No confining pressure was applied | | |

## Specimen Details

| | | | |
|---|---|---|---|
| **Specimen Reference** | C | **Stage Reference** | 1 |
| **Initial Height** | 4.21 mm | **Description** | Red Mud and Phosphogypsum Composite |
| **Initial Diameter** | 65.62 mm | **Depth within Sample** | NA |
| **Initial Moisture Content*** | 11.1 % (trimmings: 51.9 %) | **Preparation** | Soil was compacted in a 3" diameter by 5.5" long mold and the sample was allowed to dry for 96 hours prior to the test |
| **Comments** | None | | |

* Calculated from initial and dry weights of whole specimen



| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | NA |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 1C |

**Shear Conditions**

| | | | |
|---|---|---|---|
| **Rate of Axial Strain** | 0.48%/min | **Cell Pressure** | 0.0kPa |

**Conditions at Failure**

| | | | |
|---|---|---|---|
| **Failure Criterion** | Maximum Deviator Stress | | |
| **Compressive Strength** | 689.4 kPa | **Major Principal Stress ($\sigma_1$)** | 689.4 kPa |
| **Axial Strain** | 18.61% | **Minor Principal Stress ($\sigma_3$)** | 0.0 kPa |
| **Deviator Stress Correction Applied** | 0.00kPa | **Final Moisture Content** | 12.8 % |

| | |
|---|---|
| Tested By and Date: | NAJ 7/21/08 |
| Checked By and Date: | KMP 7/21/08 |
| Approved By and Date: | NAJ 8/18/08 |


Mode of Failure

Unconsolidated-Undrained Triaxial Compression Test on Cohesive (Quick Undrained)

| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | NA |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 4A |

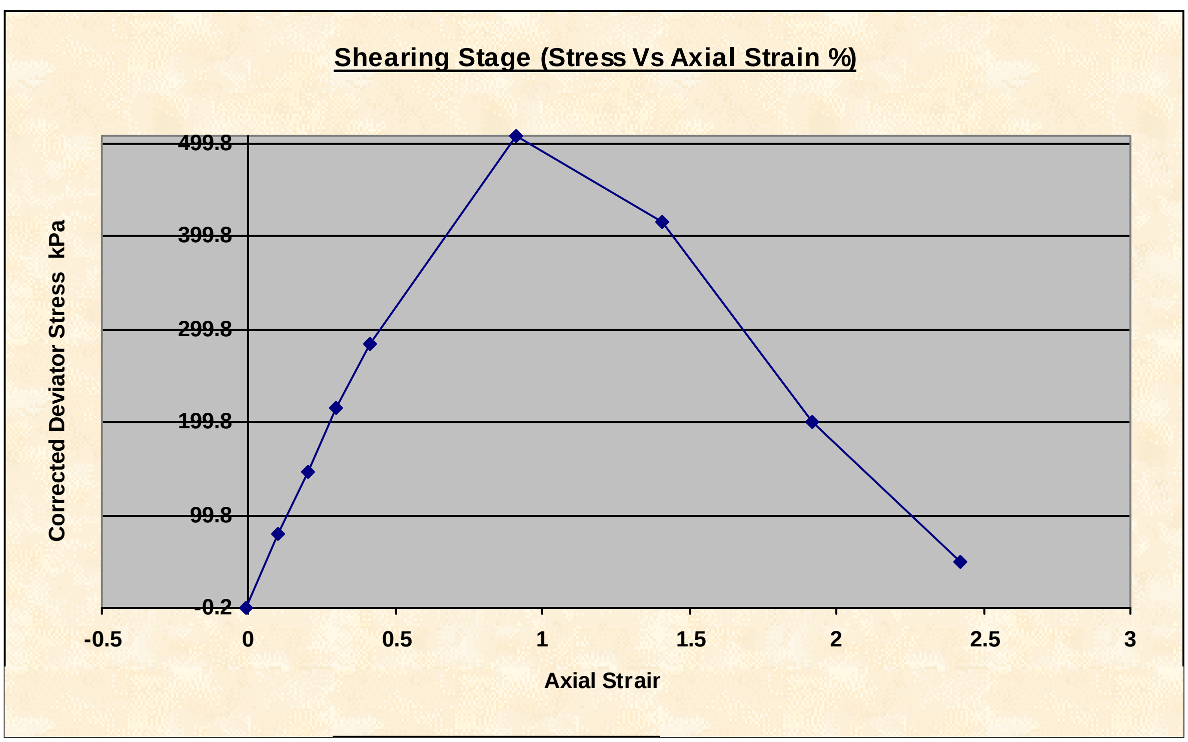
## Test & Sample Details

| | | | |
|---|---|---|---|
| **Standard** | ASTM D2850-03a | **Sample Depth** | NA |
| **Sample Type** | Small disturbed sample | **Sp. Gravity of Solids** | 2.70 |
| **Sample Description** | Aged Red Mud compacted to approx 90% max dry density at near optimum MC and air dried for 24 hours | **Lab. Temperature** | 23.0 deg.C |
| **Variations from Procedure** | No confining pressure was applied | | |

## Specimen Details

| | | | |
|---|---|---|---|
| **Specimen Reference** | A | **Stage Reference** | 1 |
| **Initial Height** | 138.94 mm | **Description** | Aged Red Mud |
| **Initial Diameter** | 70.28 mm | **Depth within Sample** | NA |
| **Initial Dry Unit Weight** | 14.24 $kN/m^3$ | **Orientation within Sample** | NA |
| **Initial Moisture Content*** | 20.6 % (trimmings: 31.2 %) | **Preparation** | Soil was compacted in a 3" diameter by 5.5" long mold and removed and air dried for 24 hours prior to test |
| **Void Ratio** | 0.86 | **Degree of Saturation** | 64.59% |
| **Comments** | None | | |

* Calculated from initial and dry weights of whole specimen



Unconsolidated-Undrained Triaxial Compression Test on Cohesive (Quick Undrained)

| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | NA |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 4A |

## Shear Conditions

| | | | |
|---|---|---|---|
| **Rate of Axial Strain** | 0.30%/min | **Cell Pressure** | 0.0kPa |

## Conditions at Failure

| | | | |
|---|---|---|---|
| **Failure Criterion** | Maximum Deviator Stress | | |
| **Compressive Strength** | 507.8 kPa | **Major Principal Stress ($\sigma_1$)** | 507.8 kPa |
| **Axial Strain** | 0.91% | **Minor Principal Stress ($\sigma_3$)** | 0.0 kPa |
| **Deviator Stress Correction Applied** | 0.00kPa | **Final Moisture Content** | 20.6 % |
| **Final Unit Weight** | 17.18 kN/m$^3$ | | |

| | |
|---|---|
| Tested By and Date: | NAJ 7/25/08 |
| Checked By and Date: | KMP 7/25/08 |
| Approved By and Date: | NAJ 8/18/08 |


Mode of Failure

Unconsolidated-Undrained Triaxial Compression Test on Cohesive (Quick Undrained)

| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | NA |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 4B |

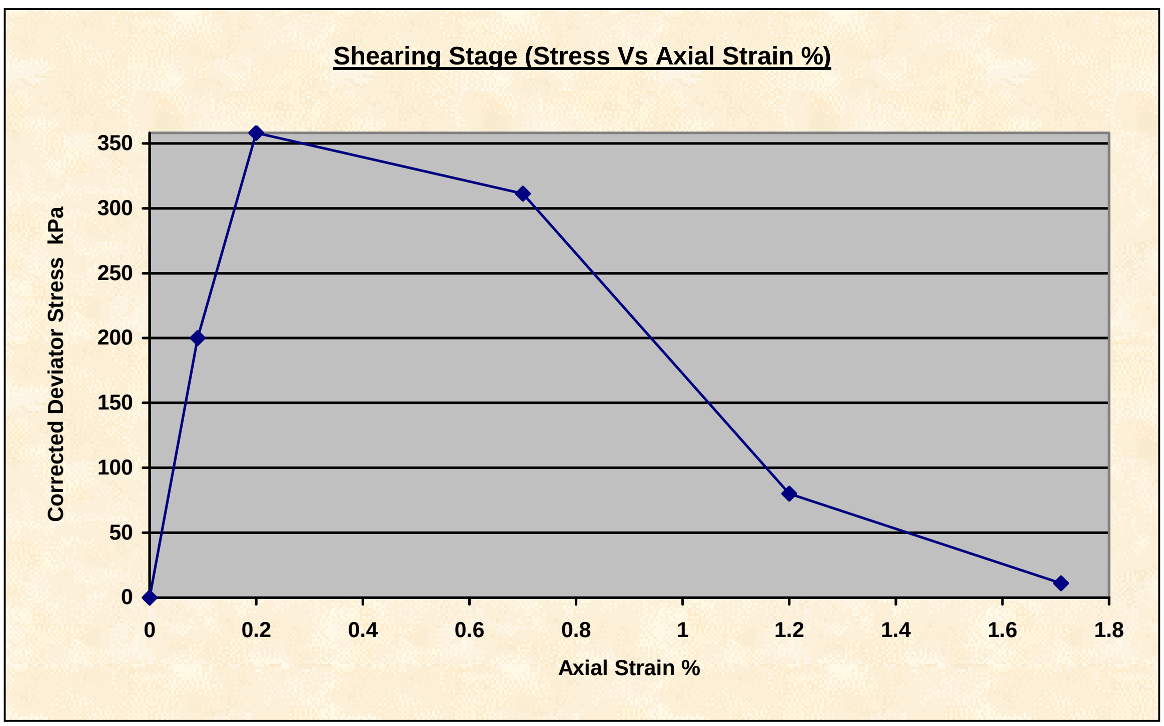
## Test & Sample Details

| | | | |
|---|---|---|---|
| **Standard** | ASTM D2850-03a | **Sample Depth** | NA |
| **Sample Type** | Small disturbed sample | **Sp. Gravity of Solids** | 2.70 |
| **Sample Description** | Aged Red Mud compacted to approx 90% max dry density at near optimum MC and air dried for 96 hours | **Lab. Temperature** | 23.0 deg.C |
| **Variations from Procedure** | No confining pressure was applied | | |

## Specimen Details

| | | | |
|---|---|---|---|
| **Specimen Reference** | B | **Stage Reference** | 1 |
| **Initial Height** | 138.76 mm | **Description** | Aged Red Mud |
| **Initial Diameter** | 70.03 mm | **Depth within Sample** | NA |
| **Initial Dry Unit Weight** | 14.31 $kN/m^3$ | **Orientation within Sample** | NA |
| **Initial Moisture Content*** | 5.5 % (trimmings: 31.2 %) | **Preparation** | Soil was compacted in a 3" by 5.5" long mold and the sample was allowed to air dry for 96 hours prior to test |
| **Void Ratio** | 0.85 | **Degree of Saturation** | 17.31% |
| **Comments** | None | | |

* Calculated from initial and dry weights of whole specimen



Unconsolidated-Undrained Triaxial Compression Test on Cohesive (Quick Undrained)

| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | NA |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 4B |

## Shear Conditions

| | | | |
|---|---|---|---|
| **Rate of Axial Strain** | 0.30%/min | **Cell Pressure** | 0.0kPa |

## Conditions at Failure

| | | | |
|---|---|---|---|
| **Failure Criterion** | Maximum Deviator Stress | | |
| **Compressive Strength** | 358.1 kPa | **Major Principal Stress ($\sigma_1$)** | 358.1 kPa |
| **Axial Strain** | 0.20% | **Minor Principal Stress ($\sigma_3$)** | 0.0 kPa |
| **Deviator Stress Correction Applied** | 0.00kPa | **Final Moisture Content** | 4.7 % |
| **Final Unit Weight** | 14.98 kN/m$^3$ | | |

| | |
|---|---|
| Tested By and Date: | NAJ 7/28/08 |
| Checked By and Date: | KMP 7/28/08 |
| Approved By and Date: | NAJ 8/18/08 |


Mode of Failure

# APPENDIX B

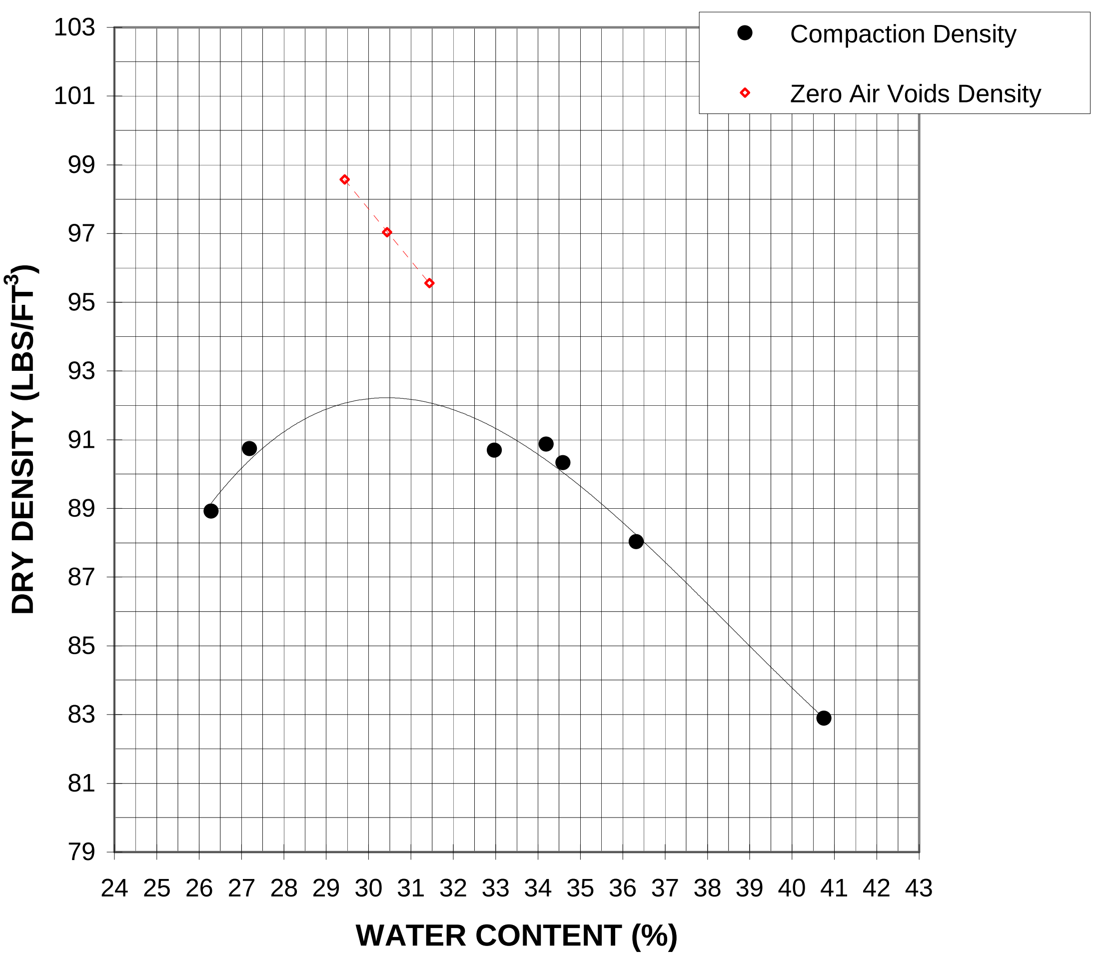
Moisture-Density Analysis

# MOISTURE-DENSITY ANALYSIS

MSE TECHNOLOGY APPLICATIONS, INC.

CLIENT: EPA/USACE
PROJECT: Red Mud/Phosphogypsum
WORK ORDER NO. LAB01.141
TEST DATE: 7/10/08
SOURCE: Process Waste Stream
DESCRIPTION: 1PGA:1RMF

SAMPLE NO.: 1
LAB I.D.: N/A
SAMPLED BY: Client
TESTED BY : NAJ/KMP
TEST METHOD: ASTM D698
Reviewed By: __________
Date: __________



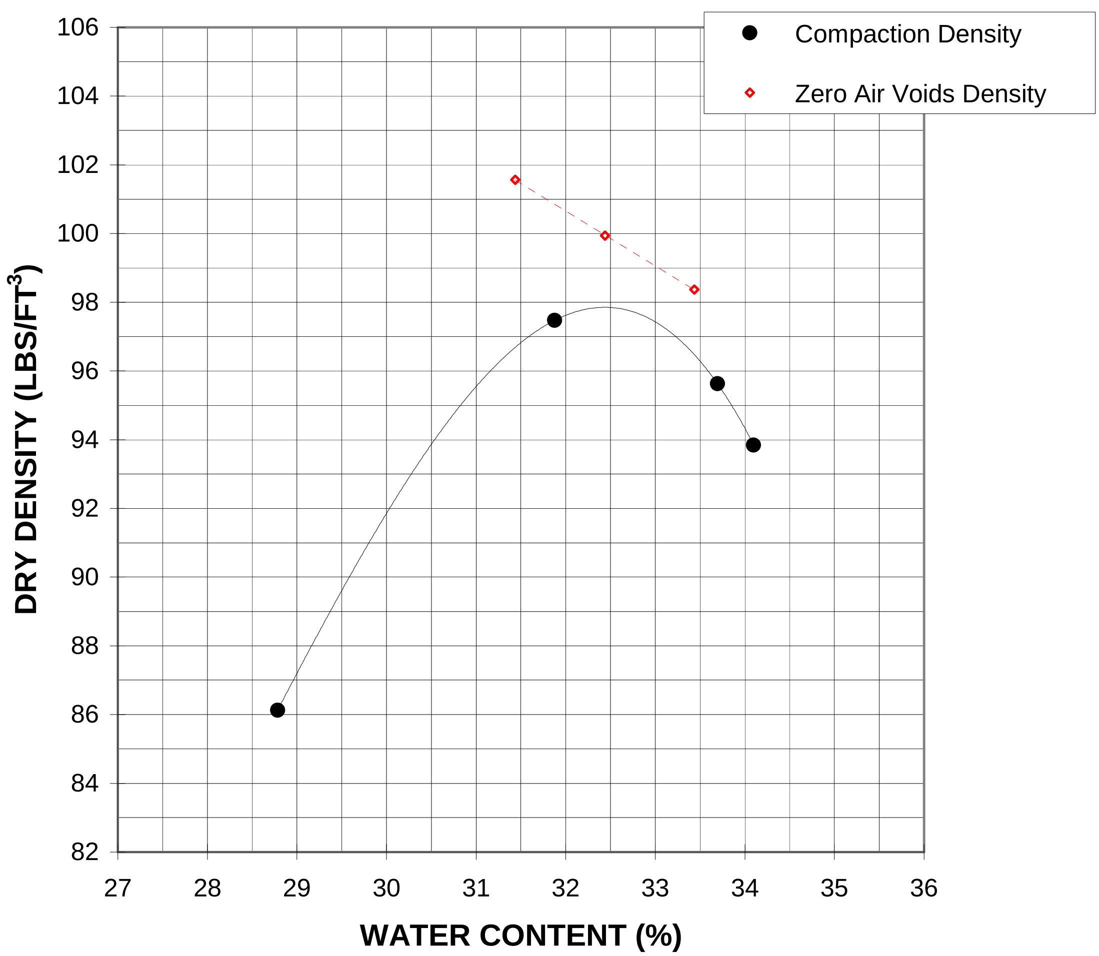

**BASE PROCTOR RESULTS**

OPTIMUM WATER CONTENT (%): 30.4
MAXIMUM DRY DEN. (LBS/FT3): 92.2

# MOISTURE-DENSITY ANALYSIS

MSE TECHNOLOGY APPLICATIONS, INC.

| | | | |
|---|---|---|---|
| CLIENT: | EPA/USACE | SAMPLE NO.: | 2 |
| PROJECT: | Red Mud/Phosphogypsum | LAB I.D.: | N/A |
| WORK ORDER NO. | LAB01.141 | SAMPLED BY: | Client |
| TEST DATE: | 7/10/08 | TESTED BY : | NAJ/KMP |
| SOURCE: | Process Waste Stream | TEST METHOD: | ASTM D698 |
| DESCRIPTION: | 1PGA:4RMA | Reviewed By: | ___________ |
| | | Date: | ___________ |




**BASE PROCTOR RESULTS**

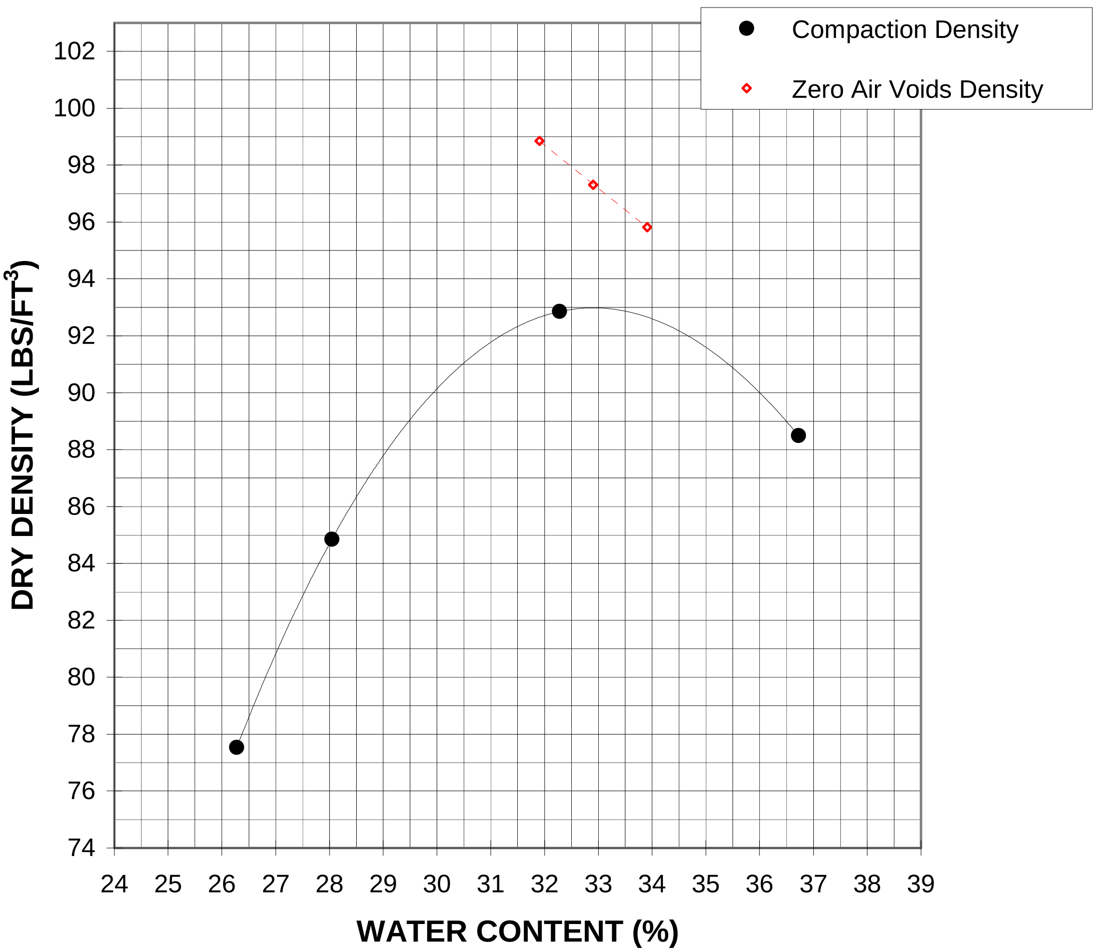
| | |
|---|---|
| OPTIMUM WATER CONTENT (%): | 32.4 |
| MAXIMUM DRY DEN. (LBS/FT3): | 97.9 |

# MOISTURE-DENSITY ANALYSIS

MSE TECHNOLOGY APPLICATIONS, INC.

CLIENT: EPA/USACE
PROJECT: Red Mud/Phosphogypsum
WORK ORDER NO. LAB01.141
TEST DATE: 7/10/08
SOURCE: Process Waste Stream
DESCRIPTION: 2PGA:3RMF

SAMPLE NO.: 3
LAB I.D.: N/A
SAMPLED BY: Client
TESTED BY : NAJ/KMP
TEST METHOD: ASTM D698
Reviewed By: ___________
Date: ___________




**BASE PROCTOR RESULTS**

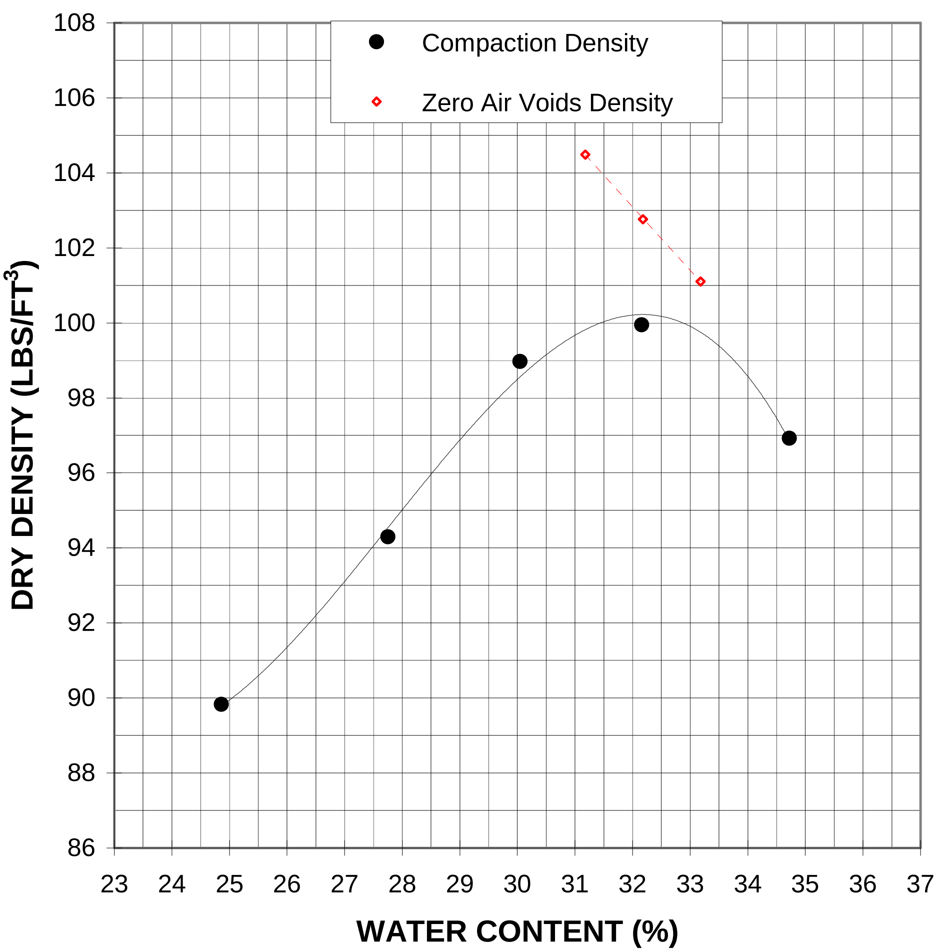
| | |
|---|---|
| OPTIMUM WATER CONTENT (%): | 32.9 |
| MAXIMUM DRY DEN. (LBS/FT3): | 93.0 |

# MOISTURE-DENSITY ANALYSIS

MSE TECHNOLOGY APPLICATIONS, INC.

CLIENT: EPA/USACE
PROJECT: Red Mud/Phosphogypsum
WORK ORDER NO. LAB01.141
TEST DATE: 7/10/08
SOURCE: Process Waste Stream
DESCRIPTION: Aged Red Mud

SAMPLE NO.: 4
LAB I.D.: N/A
SAMPLED BY: Client
TESTED BY : NAJ/KMP
TEST METHOD: ASTM D698
Reviewed By: ___________
Date: ___________




**BASE PROCTOR RESULTS**

| | |
|---|---|
| OPTIMUM WATER CONTENT (%): | 32.2 |
| MAXIMUM DRY DEN. (LBS/FT3): | 100.2 |

# APPENDIX C

Consolidation Swell Tests

One Dimensional Consolidation Properties
**(Oedometer)**

| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | NA |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Location** | MSE Geotechnical Lab | **Sample** | 3F |

## Test Details

| | | | |
|---|---|---|---|
| **Standard** | ASTM D2435-04 | **Particle Specific Gravity (Assumed)** | 2.70 |
| **Sample Type** | Small disturbed sample | **Lab. Temperature** | 24.0 deg.C |
| **Method of Testing (A/B)** | B | | |
| **Sample Description** | 1 Part PGA to 4 Parts RMA compacted to approx **90%** max dry density at near optimum MC | | |
| **Variations from Procedure** | None | | |

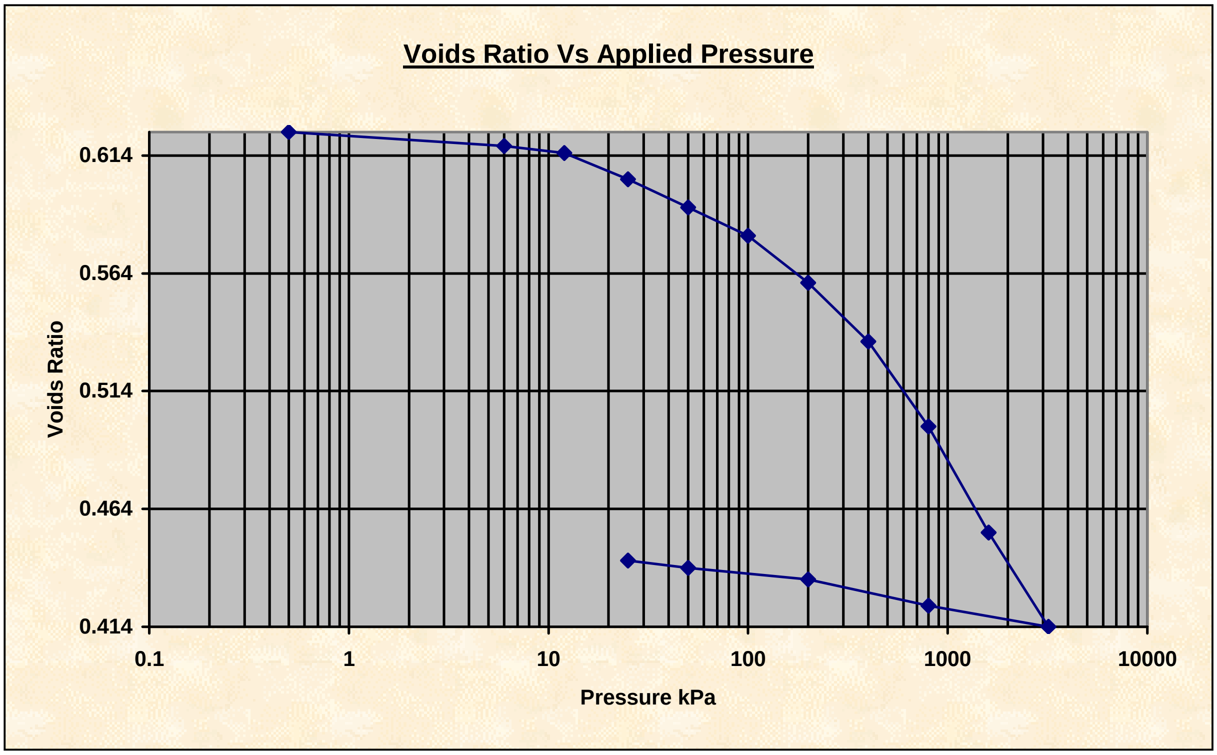
## Specimen Details

| | | | |
|---|---|---|---|
| **Specimen Reference** | A | **Description** | Red Mud and Phosphogypsum composite |
| **Depth within Sample** | NA | **Orientation within Sample** | NA |
| **Specimen Mass** | 134.75 g | **Condition** | Near Optimum Moisture |
| **Specimen Height** | 19.60 mm | **Preparation** | Soil was compacted in a 3" diameter by 5.5" long mold and the sample was pushed through the loading ring without disturbing the sample |
| **Comments** | None | | |

## Apparatus

| | | | |
|---|---|---|---|
| **Ring Number** | 1 | **Ring Diameter** | 63.44 mm |
| **Ring Height** | 19.60 mm | **Ring Weight** | 62.88 g |
| **Lever Ratio** | 10 : 1 | **Drainage** | Double-Sided |

One Dimensional Consolidation Properties
**(Oedometer)**




| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | NA |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Location** | MSE Geotechnical Lab | **Sample** | 3F |

| **Results** | |
|---|---|
| **Pre-consolidation Swell Pressure** | 0.5 kPa |
| **Preconsolidation Pressure** | 150 kPa |
| **Compression Index (Cc)** | 0.136 |
| **Rebound Index (Cr)** | 0.013 |

| | | | |
|---|---|---|---|
| **Initial Moisture Content*** | 30.8 % (trimmings: 31.6 %) | **Final Moisture Content** | 27.7 % |
| **Initial Bulk Density** | 2.18 $Mg/m^3$ | **Final Bulk Density** | 2.39 $Mg/m^3$ |
| **Initial Dry Density** | 1.66 $Mg/m^3$ | **Final Dry Density** | 1.87 $Mg/m^3$ |
| **Initial Void Ratio** | 0.6238 | **Final Void Ratio** | 0.4421 |

* Calculated from initial and dry weights of whole specimen

One Dimensional Consolidation Properties
**(Oedometer)**

| Pressure (Loading) | Load Increment Duration | Deformation (Corrected) | $d_{100}$ (Corrected) | Coefficient of Consolidation ($c_v$) |
|---|---|---|---|---|
| **0.00** | | | | |
| 6.0 kPa | 240.000 min | 0.075 mm | 0.071 mm | 8.85 $mm^2$/min |
| 12.0 kPa | 762.000 min | 0.104 mm | 0.105 mm | 21.91 $mm^2$/min |
| 25.0 kPa | 2640.000 min | 0.235 mm | 0.224 mm | 39.72 $mm^2$/min |
| 50.0 kPa | 480.000 min | 0.387 mm | 0.378 mm | 5.78 $mm^2$/min |
| 100.0 kPa | 762.000 min | 0.523 mm | 0.517 mm | 3.04 $mm^2$/min |
| 200.0 kPa | 605.000 min | 0.767 mm | 0.756 mm | 8.46 $mm^2$/min |
| 400.0 kPa | 762.000 min | 1.069 mm | 1.063 mm | 7.74 $mm^2$/min |
| 800.0 kPa | 605.000 min | 1.511 mm | 1.500 mm | 10.10 $mm^2$/min |
| 1600.0 kPa | 762.000 min | 2.048 mm | 2.037 mm | 6.87 $mm^2$/min |
| 3200.0 kPa | 1260.000 min | 2.537 mm | 2.531 mm | 3.47 $mm^2$/min |
| 800.0 kPa | 240.000 min | 2.425 mm | --------- | --------- |
| 200.0 kPa | 1080.000 min | 2.292 mm | --------- | --------- |
| 50.0 kPa | 190.000 min | 2.226 mm | --------- | --------- |
| 25.0 kPa | 151.000 min | 2.193 mm | --------- | --------- |

| **Method of Time Fitting Used** | Log Time |
|---|---|

| | |
|---|---|
| Tested By and Date: | NAJ 7/25/08 |
| Checked By and Date: | KMP 7/25/08 |
| Approved By and Date: | NAJ 8/18/08 |

# APPENDIX D

Unconsolidated-Undrained Triaxial Compression Test on Cohesive Soils

**Unconsolidated-Undrained Triaxial Compression Test on Coh**
**(Quick Undrained)**

| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | NA |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 3A |

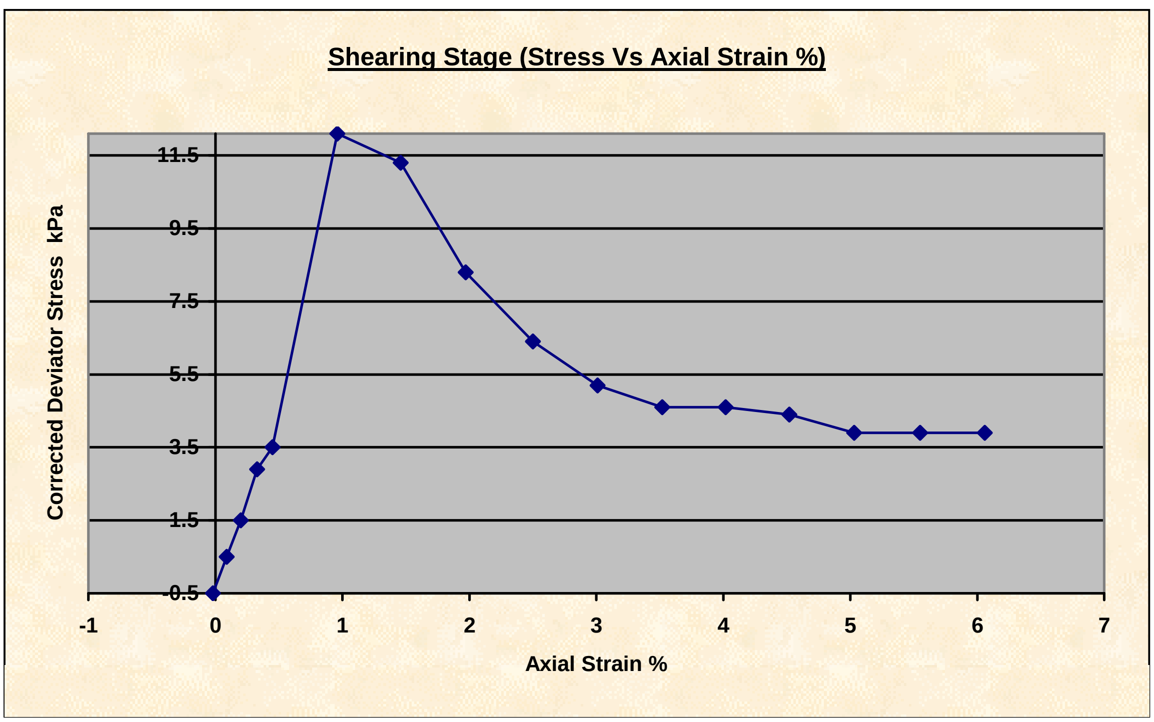
## Test & Sample Details

| | | | |
|---|---|---|---|
| **Standard** | ASTM D2850-03a | **Sample Depth** | NA |
| **Sample Type** | Small disturbed sample | **Sp. Gravity of Solids** | 2.70 |
| **Sample Description** | 1 Part PGA to 4 Parts RMA compacted to approx 90 percent of dry max density at near optimum MC | **Lab. Temperature** | 30.0 deg.C |
| **Variations from Procedure** | None | | |

## Specimen Details

| | | | |
|---|---|---|---|
| **Specimen Reference** | A | **Stage Reference** | 1 |
| **Initial Height** | 136.53 mm | **Description** | Red Mud and Phosphogypsum composite |
| **Initial Diameter** | 71.42 mm | **Depth within Sample** | NA |
| **Initial Dry Unit Weight** | 14.19 $kN/m^3$ | **Orientation within Sample** | NA |
| **Initial Moisture Content*** | 33.4 % (trimmings: 30.5 %) | **Preparation** | Soil was compacted in a 3" by 5.5" long mold with a rubber membrane |
| **Void Ratio** | 0.87 | **Degree of Saturation** | 104.09% |
| **Comments** | None | | |

* Calculated from initial and dry weights of whole specimen



**Unconsolidated-Undrained Triaxial Compression Test on Coh**
**(Quick Undrained)**

| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | NA |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 3A |

## Shear Conditions

| | | | |
|---|---|---|---|
| **Rate of Axial Strain** | 1.00%/min | **Cell Pressure** | 13.9kPa |

## Conditions at Failure

| | | | |
|---|---|---|---|
| **Failure Criterion** | Maximum Deviator Stress | | |
| **Compressive Strength** | 12.1 kPa | **Major Principal Stress ($\sigma_1$)** | 26.0 kPa |
| **Axial Strain** | 0.96% | **Minor Principal Stress ($\sigma_3$)** | 13.9 kPa |
| **Deviator Stress Correction Applied** | 0.00kPa | **Final Moisture Content** | 37.5 % |
| **Final Unit Weight** | 19.51 kN/m$^3$ | | |

| | |
|---|---|
| Tested By and Date: | NAJ 7/21/08 |
| Checked By and Date: | KMP 7/21/08 |
| Approved By and Date: | NAJ 8/18/08 |


Mode of Failure

**Unconsolidated-Undrained Triaxial Compression Test on Coh**
**(Quick Undrained)**

| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | NA |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 3B |

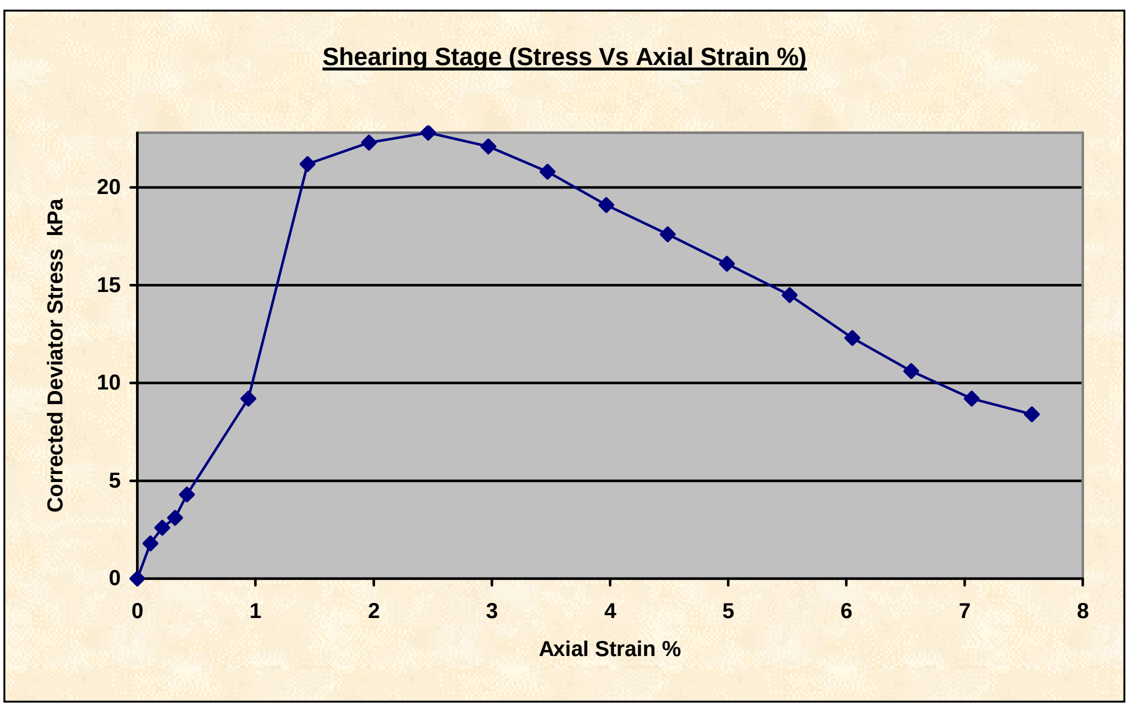
## Test & Sample Details

| | | | |
|---|---|---|---|
| **Standard** | ASTM D2850-03a | **Sample Depth** | NA |
| **Sample Type** | Small disturbed sample | **Sp. Gravity of Solids** | 2.70 |
| **Sample Description** | 1 Part PGA to 4 Parts RMA compacted to approx 90 percent of dry max density at near optimum MC | **Lab. Temperature** | 30.0 deg.C |
| **Variations from Procedure** | None | | |

## Specimen Details

| | | | |
|---|---|---|---|
| **Specimen Reference** | B | **Stage Reference** | 1 |
| **Initial Height** | 136.53 mm | **Description** | Red Mud and Phosphogypsum Composite |
| **Initial Diameter** | 71.12 mm | **Depth within Sample** | 0.00 mm |
| **Initial Dry Unit Weight** | 14.56 kN/m3 | **Orientation within Sample** | |
| **Initial Moisture Content*** | 31.0 % (trimmings: 30.5 %) | **Preparation** | Soil was compacted in a 3" by 5.5" long mold with a rubber membrane |
| **Void Ratio** | 0.82 | **Degree of Saturation** | 102.15% |
| **Comments** | None | | |

* Calculated from initial and dry weights of whole specimen



**Unconsolidated-Undrained Triaxial Compression Test on Coh**
**(Quick Undrained)**

| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | NA |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 3B |

## Shear Conditions

| | | | |
|---|---|---|---|
| **Rate of Axial Strain** | 1.00%/min | **Cell Pressure** | 34.3kPa |

## Conditions at Failure

| | | | |
|---|---|---|---|
| **Failure Criterion** | Maximum Deviator Stress | | |
| **Compressive Strength** | 22.8 kPa | **Major Principal Stress ($\sigma_1$)** | 57.2 kPa |
| **Axial Strain** | 2.46% | **Minor Principal Stress ($\sigma_3$)** | 34.3 kPa |
| **Deviator Stress Correction Applied** | 0.00kPa | **Final Moisture Content** | 34.4 % |
| **Final Unit Weight** | 19.57 kN/m3 | | |

| | |
|---|---|
| Tested By and Date: | NAJ 07/21/08 |
| Checked By and Date: | KMP 07/21/08 |
| Approved By and Date: | NAJ 8/18/08 |


Mode of Failure

# APPENDIX E

Consolidated-Undrained Test Data

Consolidated Undrained Triaxial Compression Test
**with measurement of Pore Pressure**

| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | NA |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 3F-4 |

| Test Details | | | |
|---|---|---|---|
| **Standard** | ASTM D4767-04 | **Particle Density** | 2.70 Mg/m$^3$ (Assumed) |
| **Test Definition** | Consolidated Undrained | **Drainage location** | Bottom |
| **Sample Type** | Small disturbed sample | **Lab. Temperature** | 24.0 deg.C |
| **Sample Description** | 1 Part PGA to 4 Parts RMA compacted to approx 90 percent of dry max density at near optimum MC | | |
| **Variations from Procedure** | None | | |

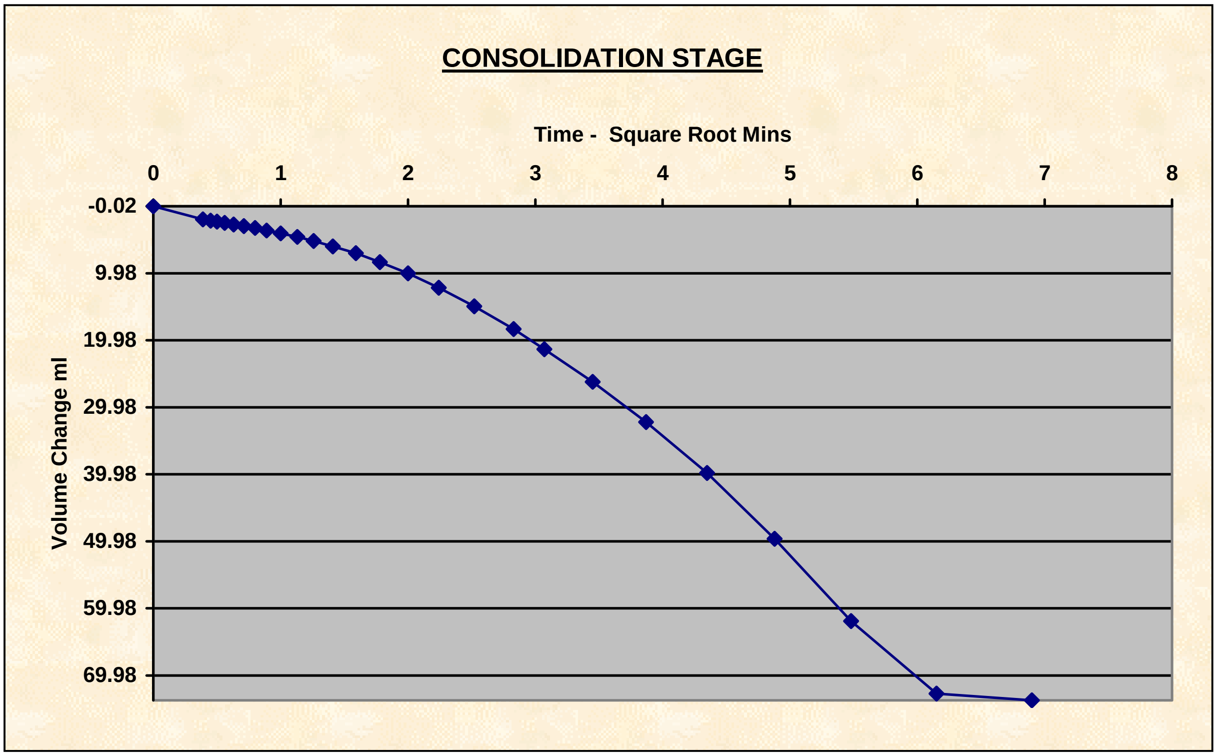
| Specimen Details | | | |
|---|---|---|---|
| **Specimen Reference** | A | **Description** | Red Mud and Phosphogypsum Compsosite |
| **Depth within Sample** | NA | **Orientation within Sample** | NA |
| **Initial Height** | 141.12 mm | **Initial Diameter** | 70.41 mm |
| **Preparation** | Soil was compacted in a 3" diameter by 5.5" long mold | **Moisture Content** | 29.2 % (trimmings: 31.6 %) |
| **Bulk Density** | 1.86 Mg/m$^3$ | **Membrane Thickness** | 0.41 mm |
| **Comments** | None | | |

## SATURATION STAGE

| | | | |
|---|---|---|---|
| **Saturation Method** | Cell/Back Pressure Increments | **Cell Increments** | 68.9kPa |
| **Final Cell Pressure** | 550.7kPa | **Δ Pore Pressure** | Approximately 70 kPa |
| **Final B Value** | Approximately 1.0, sample considered saturated | | |

Consolidated Undrained Triaxial Compression Test
**with measurement of Pore Pressure**

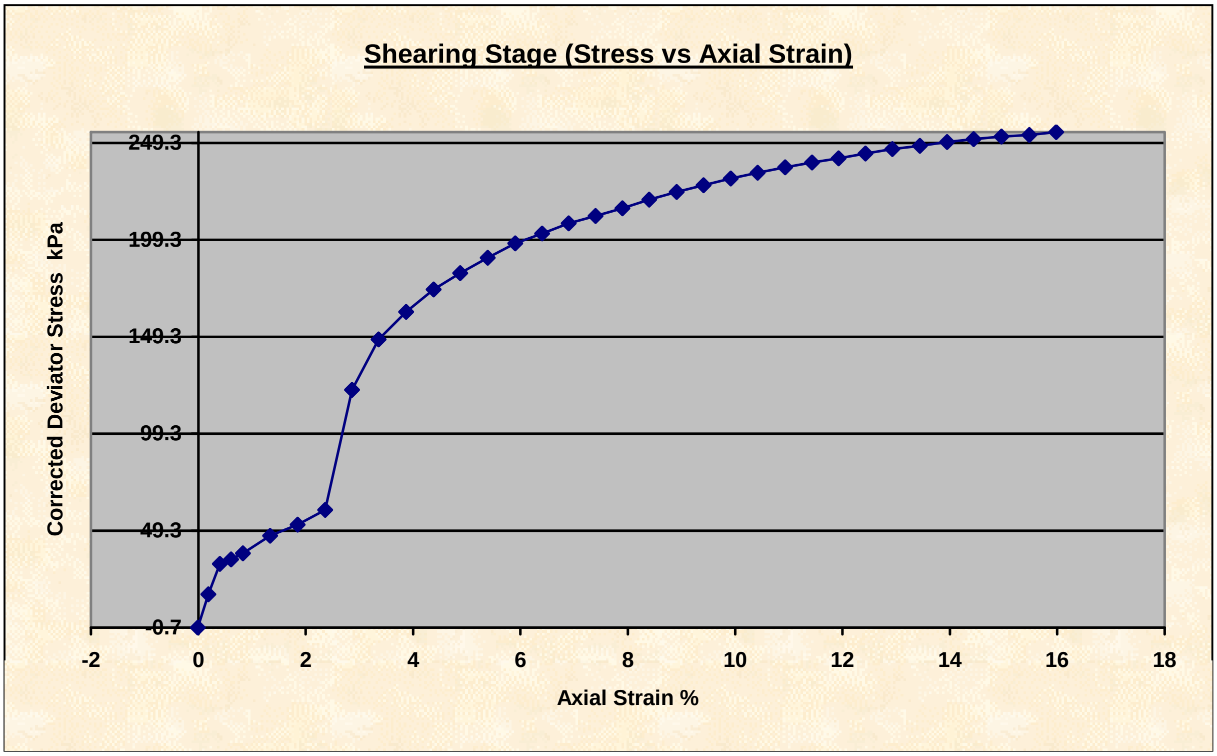
| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | NA |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 3F-4 |

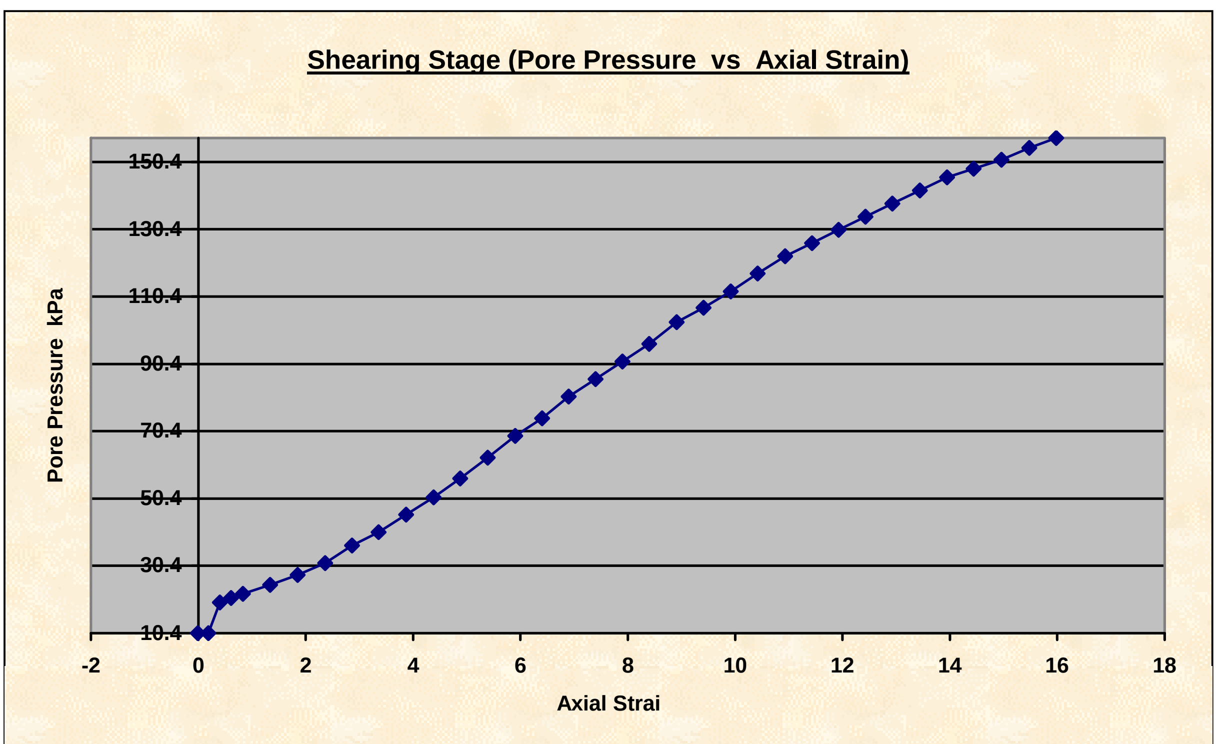



| | | | |
|---|---|---|---|
| **Cell Pressure** | 405.6kPa | **Back Pressure** | 350.1kPa |
| **Effective Pressure** | 55.5kPa | **Final Pore Pressure** | 6.2 kPa |

Consolidated Undrained Triaxial Compression Test
**with measurement of Pore Pressure**

| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | NA |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 3F-4 |



Consolidated Undrained Triaxial Compression Test
**with measurement of Pore Pressure**

| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | NA |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 3F-4 |

## Shear Conditions

| | | | |
|---|---|---|---|
| **Rate of Axial Displacement** | 0.0531mm/min | **Cell Pressure** | 316.0kPa |
| **Initial Back Pressure** | 260.8kPa | **Effective Stress at Start of Stage** | 55.2kPa |

## Conditions at Failure

| | | | |
|---|---|---|---|
| **Failure Criterion** | Maximum Deviator Stress | | |
| **Pore Pressure** | 151.0kPa | **Minor Effective Principal Stress ($\sigma'_3$)** | 165.0kPa |
| **Deviator Stress ($\sigma'_1$-$\sigma'_3$)** | 252.6kPa | **Major Effective Principal Stress ($\sigma'_1$)** | 417.5kPa |
| **Axial Strain** | 14.96% | **Effective Principal Stress Ratio** | 2.531 |
| **Deviator Stress Correction** | 1.8kPa | | |
| **Density** | 2.16 Mg/m$^3$ | **Moisture Content** | 30.2 % |

| | |
|---|---|
| Tested By and Date: | NAJ 8/2/08 |
| Checked By and Date: | KMP 8/2/08 |
| Approved By and Date: | NAJ 8/18/08 |

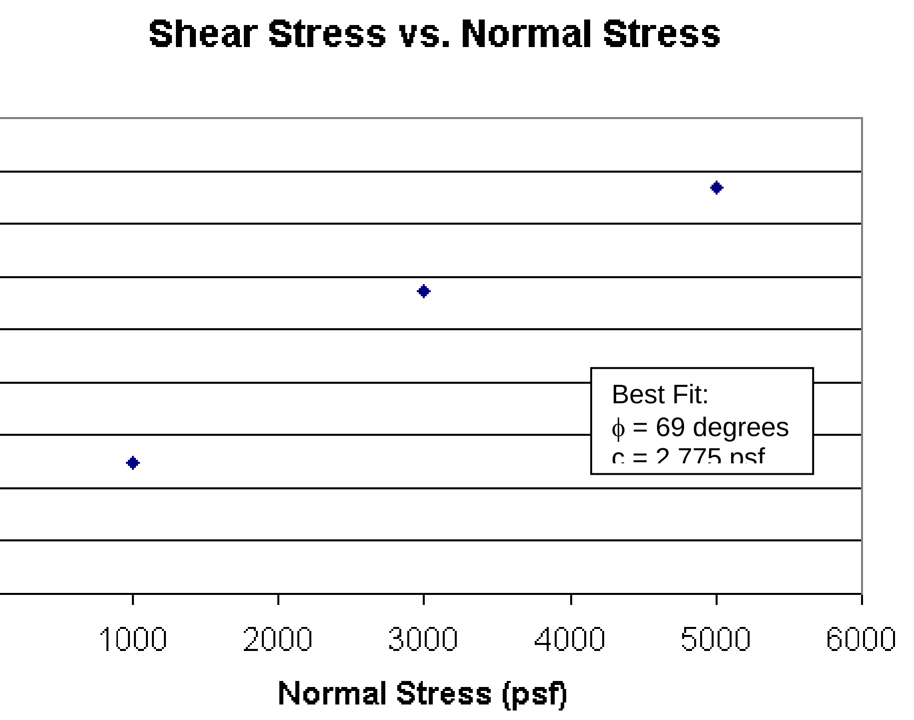

Photo after failure

# APPENDIX F

CD/Direct Shear Test Data

**Direct Shear Test**
**ASTM D3080-04**

Client; MSE Technology Applications
Project: Beneficial Use of Red Mud and Phosphogypsum
Job: LAB01.141

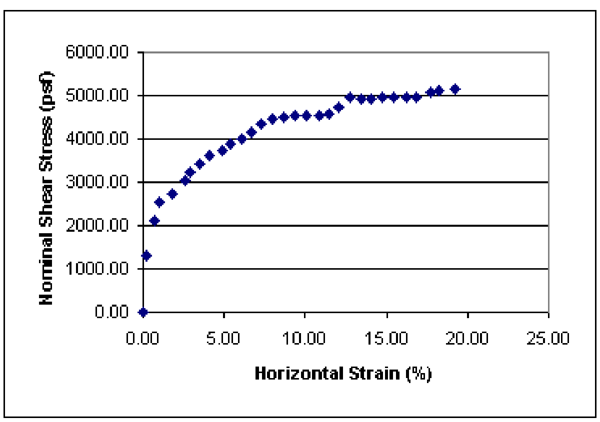


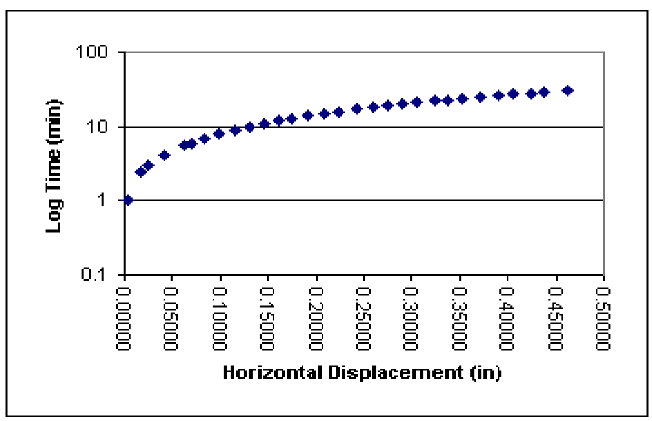

| Max Nominal Shear Stress (psf) | Normal Stress (psf) |
|---|---|
| 4,943 | 1000 |
| 11,450 | 3000 |
| 15,350 | 5000 |

| Time (min) | Vertical Displacement (in) | Vertical Displacement (in) |
|---|---|---|
| | Gage: Soil test 0.001range | Gage: Soil test 0.001range |
| 0 | 0.1960 | 0.0000 |
| 5 | 0.4835 | 0.2875 |
| 10 | 0.4850 | 0.2890 |
| 15 | 0.4850 | 0.2890 |
| 20 | 0.4860 | 0.2900 |
| 25 | 0.4865 | 0.2905 |
| 30 | 0.4870 | 0.2910 |
| 35 | 0.4873 | 0.2913 |
| 40 | 0.4885 | 0.2925 |
| 45 | 0.4890 | 0.2930 |

| Constants | |
|---|---|
| Rate | 0.5mm/min |
| Diameter sample | 2.4in |
| Diameter sample | 0.20ft |
| Proving ring cal. | 3210lbs/in |
| Cross sec. Area | 0.0314ft2 |
| Vertical Load | 31.4lbs/in |
| Vertical Load | 14.24280042kg |
| Normal Stress | 1000psf |

| Time (min) | Horizontal Displacement (in) | Adjusted Horizontal Displacement (in) | Strain (%) | Shearing Force (in) | Adjusted Shearing Force (in) | Shear force (lbs) | Nominal Shear Stress (psf) |
|---|---|---|---|---|---|---|---|
| | | Gage: Soil Test 2" range | | | Gage: Soil Test 0.0001" range | Nick's | |
| | | | | | | | |
| 0.001 | 0.87200 | 0.00000 | 0.00 | 0.09715 | 0.00000 | 0.00 | 0.00 |
| 1 | 0.87600 | 0.00400 | 0.17 | 0.00990 | 0.01275 | 40.93 | 1303.42 |
| 2.5 | 0.88900 | 0.01700 | 0.71 | 0.01770 | 0.02055 | 65.97 | 2100.81 |
| 3 | 0.89700 | 0.02500 | 1.04 | 0.02180 | 0.02465 | 79.13 | 2519.95 |
| 4 | 0.91400 | 0.04200 | 1.75 | 0.02380 | 0.02665 | 85.55 | 2724.41 |
| 5.5 | 0.93500 | 0.06300 | 2.63 | 0.02680 | 0.02965 | 95.18 | 3031.10 |
| 6 | 0.94200 | 0.07000 | 2.92 | 0.02865 | 0.03150 | 101.12 | 3220.22 |
| 7 | 0.95500 | 0.08300 | 3.46 | 0.03050 | 0.03335 | 107.05 | 3409.35 |
| 8 | 0.97100 | 0.09900 | 4.13 | 0.03240 | 0.03525 | 113.15 | 3603.58 |
| 9 | 0.98800 | 0.11600 | 4.83 | 0.03360 | 0.03645 | 117.00 | 3726.26 |
| 10 | 0.00200 | 0.13000 | 5.42 | 0.03500 | 0.03785 | 121.50 | 3869.38 |
| 11 | 0.01750 | 0.14550 | 6.06 | 0.03610 | 0.03895 | 125.03 | 3981.83 |
| 12 | 0.03250 | 0.16050 | 6.69 | 0.03780 | 0.04065 | 130.49 | 4155.62 |
| 13 | 0.04650 | 0.17450 | 7.27 | 0.03960 | 0.04245 | 136.26 | 4339.63 |
| 14 | 0.06350 | 0.19150 | 7.98 | 0.04070 | 0.04355 | 139.80 | 4452.09 |
| 15 | 0.08000 | 0.20800 | 8.67 | 0.04130 | 0.04415 | 141.72 | 4513.42 |
| 16 | 0.09600 | 0.22400 | 9.33 | 0.04165 | 0.04450 | 142.85 | 4549.20 |
| 17 | 0.11400 | 0.24200 | 10.08 | 0.04165 | 0.04450 | 142.85 | 4549.20 |
| 18 | 0.13200 | 0.26000 | 10.83 | 0.04170 | 0.04455 | 143.01 | 4554.32 |
| 19 | 0.14650 | 0.27450 | 11.44 | 0.04205 | 0.04490 | 144.13 | 4590.10 |
| 20 | 0.16200 | 0.29000 | 12.08 | 0.04330 | 0.04615 | 148.14 | 4717.88 |
| 21 | 0.17700 | 0.30500 | 12.71 | 0.04550 | 0.04835 | 155.20 | 4942.79 |
| 22 | 0.19550 | 0.32350 | 13.48 | 0.04525 | 0.04810 | 154.40 | 4917.23 |
| 23 | 0.20900 | 0.33700 | 14.04 | 0.04535 | 0.04820 | 154.72 | 4927.45 |
| 24 | 0.22500 | 0.35300 | 14.71 | 0.04550 | 0.04835 | 155.20 | 4942.79 |
| 25 | 0.24350 | 0.37150 | 15.48 | 0.04550 | 0.04835 | 155.20 | 4942.79 |
| 26 | 0.26200 | 0.39000 | 16.25 | 0.04560 | 0.04845 | 155.52 | 4953.01 |
| 27 | 0.27700 | 0.40500 | 16.88 | 0.04560 | 0.04845 | 155.52 | 4953.01 |
| 28 | 0.29700 | 0.42500 | 17.71 | 0.04680 | 0.04965 | 159.38 | 5075.68 |
| 29 | 0.31000 | 0.43800 | 18.25 | 0.04705 | 0.04990 | 160.18 | 5101.24 |
| 30.5 | 0.33350 | 0.46150 | 19.23 | 0.04750 | 0.05035 | 161.62 | 5147.25 |
| | | | | Shear Stress at Failure = | | | 4,943 |

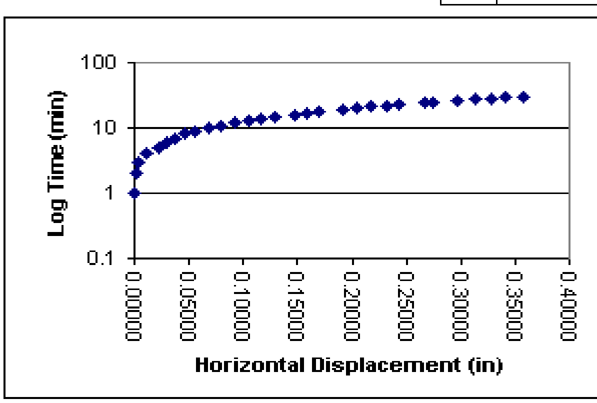


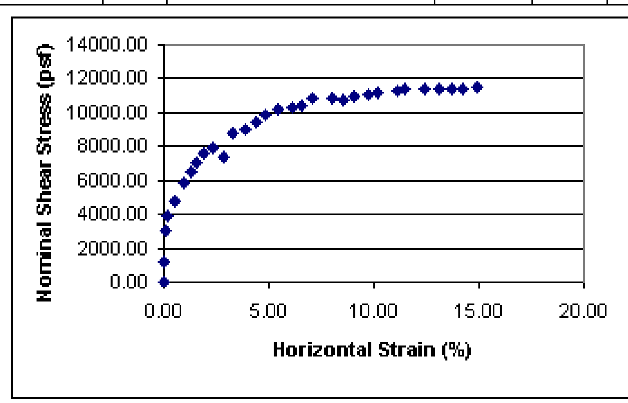



| Time (min) | Vertical Displacement (in) | Adjusted Vertical Displacement (in) |
|---|---|---|
| | Gage: Soil test 0.001range | Gage: Soil test 0.001range |
| 0 | 0.1045 | 0.0000 |
| 5 | 0.4990 | 0.3945 |
| 10 | 0.5005 | 0.3960 |
| 15 | 0.5013 | 0.3968 |
| 20 | 0.5020 | 0.3975 |
| 25 | 0.5023 | 0.3978 |
| 30 | 0.5028 | 0.3983 |
| 35 | 0.5030 | 0.3985 |
| 40 | 0.5035 | 0.3990 |
| 45 | 0.5038 | 0.3993 |

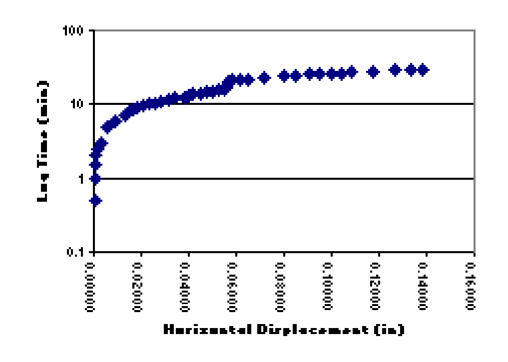
| Constants | |
|---|---|
| Rate | 0.5 mm/min |
| Diameter sample | 2.4 in |
| Diameter sample | 0.20 ft |
| Proving ring cal. | 3210 lbs/in |
| Cross sec. Area | 0.0314 ft2 |
| Vertical Load | 94.2 lbs/in |
| Vertical Load | 42.72840125 kg |
| Normal Stress | 3000 psf |

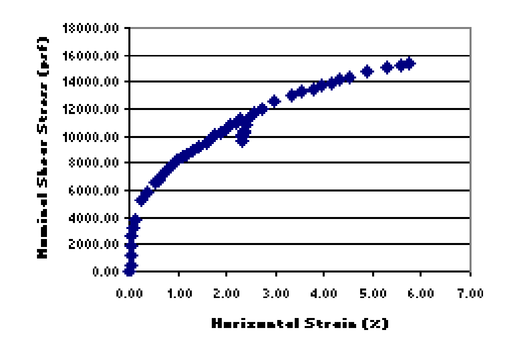
| Time (min) | Horizontal Displacement (in) | Adjusted Horizontal Displacement (in) | Strain (%) | Shearing Force (in) | Adjusted Shearing Force (in) | Shear force (lbs) | Nominal Shear Stress (psf) |
|---|---|---|---|---|---|---|---|
| | | Gage: Soil Test 2" range | | | Gage: Soil Test 0.0001" range | Nick's | |
| | | | | | | | |
| 0 | 0.96800 | 0.00000 | 0.00 | 0.09850 | 0.00000 | 0.00 | 0.00 |
| 1 | 0.96850 | 0.00050 | 0.02 | 0.01050 | 0.01200 | 38.52 | 1226.75 |
| 2 | 0.97000 | 0.00200 | 0.08 | 0.02850 | 0.03000 | 96.30 | 3066.88 |
| 3 | 0.97250 | 0.00450 | 0.19 | 0.03700 | 0.03850 | 123.59 | 3935.83 |
| 4 | 0.97950 | 0.01150 | 0.48 | 0.04500 | 0.04650 | 149.27 | 4753.66 |
| 5 | 0.99000 | 0.02200 | 0.92 | 0.05600 | 0.05750 | 184.58 | 5878.18 |
| 6 | 0.99800 | 0.03000 | 1.25 | 0.06250 | 0.06400 | 205.44 | 6542.68 |
| 7 | 0.00450 | 0.03650 | 1.52 | 0.06740 | 0.06890 | 221.17 | 7043.60 |
| 8 | 0.01450 | 0.04650 | 1.94 | 0.07270 | 0.07420 | 238.18 | 7585.41 |
| 9 | 0.02300 | 0.05500 | 2.29 | 0.07650 | 0.07800 | 250.38 | 7973.89 |
| 10 | 0.03550 | 0.06750 | 2.81 | 0.07040 | 0.07190 | 230.80 | 7350.29 |
| 11 | 0.04750 | 0.07950 | 3.31 | 0.08410 | 0.08560 | 274.78 | 8750.83 |
| 12 | 0.06100 | 0.09300 | 3.88 | 0.08710 | 0.08860 | 284.41 | 9057.52 |
| 13 | 0.07250 | 0.10450 | 4.35 | 0.09100 | 0.09250 | 296.93 | 9456.21 |
| 14 | 0.08400 | 0.11600 | 4.83 | 0.09500 | 0.09650 | 309.77 | 9865.13 |
| 15 | 0.09750 | 0.12950 | 5.40 | 0.09790 | 0.09940 | 319.07 | 10161.59 |
| 16 | 0.11500 | 0.14700 | 6.13 | 0.09890 | 0.10040 | 322.28 | 10263.82 |
| 17 | 0.12600 | 0.15800 | 6.58 | 0.00070 | 0.10220 | 328.06 | 10447.83 |
| 18 | 0.13800 | 0.17000 | 7.08 | 0.00490 | 0.10640 | 341.54 | 10877.20 |
| 19 | 0.16000 | 0.19200 | 8.00 | 0.00470 | 0.10620 | 340.90 | 10856.75 |
| 20 | 0.17300 | 0.20500 | 8.54 | 0.00380 | 0.10530 | 338.01 | 10764.75 |
| 21 | 0.18600 | 0.21800 | 9.08 | 0.00540 | 0.10690 | 343.15 | 10928.31 |
| 22 | 0.20100 | 0.23300 | 9.71 | 0.00650 | 0.10800 | 346.68 | 11040.76 |
| 23 | 0.21200 | 0.24400 | 10.17 | 0.00750 | 0.10900 | 349.89 | 11142.99 |
| 24 | 0.23450 | 0.26650 | 11.10 | 0.00920 | 0.11070 | 355.35 | 11316.78 |
| 25 | 0.24350 | 0.27550 | 11.48 | 0.01015 | 0.11165 | 358.40 | 11413.90 |
| 26 | 0.26500 | 0.29700 | 12.38 | 0.01015 | 0.11165 | 358.40 | 11413.90 |
| 27 | 0.28200 | 0.31400 | 13.08 | 0.01010 | 0.11160 | 358.24 | 11408.79 |
| 28 | 0.29600 | 0.32800 | 13.67 | 0.01010 | 0.11160 | 358.24 | 11408.79 |
| 29 | 0.30900 | 0.34100 | 14.21 | 0.01030 | 0.11180 | 358.88 | 11429.24 |
| 30 | 0.32500 | 0.35700 | 14.88 | 0.01050 | 0.11200 | 359.52 | 11449.68 |
| | | | | Shear Stress at Failure = | | | 11,450 |



| Time (min) | Vertical Displacement (in) | Adjusted Vertical Displacement (in) |
|---|---|---|
| | Gage: Soil test 0.001range | Gage: Soil test 0.001range |
| 0.001 | 0.3640 | 0.0000 |
| 5 | 0.6890 | 0.3250 |
| 10 | 0.6910 | 0.3270 |
| 15 | 0.6920 | 0.3280 |
| 20 | 0.6930 | 0.3290 |
| 25 | 0.6940 | 0.3300 |
| 30 | 0.6945 | 0.3305 |
| 35 | 0.6945 | 0.3305 |




| Constants | |
|---|---|

| Time (min) | Horizontal Displacement (in) | Adjusted Horizontal Displacement (in) | Strain (%) | Shearing Force (in) | Adjusted Shearing Force (in) | Shear force (lbs) | Nominal Shear Stress (psf) |
|---|---|---|---|---|---|---|---|
| | Gage: Soil Test 2" range | | | Gage: Soil Test 0.0001" range | Nick's | | |
| | | | | | | | |
| 0 | 0.91000 | 0.00000 | 0.00 | 0.09755 | 0.00000 | 0.00 | 0.00 |
| 0.5 | 0.91050 | 0.00050 | 0.02 | 0.00200 | 0.00445 | 14.28 | 454.92 |
| 1 | 0.91075 | 0.00075 | 0.03 | 0.00900 | 0.01145 | 36.75 | 1170.53 |
| 1.5 | 0.91075 | 0.00075 | 0.03 | 0.01600 | 0.01845 | 59.22 | 1886.13 |
| 2 | 0.91100 | 0.00100 | 0.04 | 0.02300 | 0.02545 | 81.69 | 2601.74 |
| 2.5 | 0.91150 | 0.00150 | 0.06 | 0.02950 | 0.03195 | 102.56 | 3266.23 |
| 3 | 0.91300 | 0.00300 | 0.13 | 0.03500 | 0.03745 | 120.21 | 3828.49 |
| 5 | 0.91550 | 0.00550 | 0.23 | 0.04850 | 0.05095 | 163.55 | 5208.58 |
| 6 | 0.91900 | 0.00900 | 0.38 | 0.05550 | 0.05795 | 186.02 | 5924.19 |
| 7 | 0.92300 | 0.01300 | 0.54 | 0.06180 | 0.06425 | 206.24 | 6568.23 |
| 7.5 | 0.92450 | 0.01450 | 0.60 | 0.06350 | 0.06595 | 211.70 | 6742.02 |
| 8 | 0.92500 | 0.01500 | 0.63 | 0.06490 | 0.06735 | 216.19 | 6885.14 |
| 8.5 | 0.92650 | 0.01650 | 0.69 | 0.06790 | 0.07035 | 225.82 | 7191.83 |
| 9 | 0.92850 | 0.01850 | 0.77 | 0.07100 | 0.07345 | 235.77 | 7508.74 |
| 9.5 | 0.93050 | 0.02050 | 0.85 | 0.07400 | 0.07645 | 245.40 | 7815.43 |
| 10 | 0.93350 | 0.02350 | 0.98 | 0.07700 | 0.07945 | 255.03 | 8122.12 |
| 10.5 | 0.93600 | 0.02600 | 1.08 | 0.07990 | 0.08235 | 264.34 | 8418.58 |
| 11 | 0.93850 | 0.02850 | 1.19 | 0.08260 | 0.08505 | 273.01 | 8694.60 |
| 11.5 | 0.94150 | 0.03150 | 1.31 | 0.08530 | 0.08775 | 281.68 | 8970.62 |
| 12 | 0.94450 | 0.03450 | 1.44 | 0.08800 | 0.09045 | 290.34 | 9246.64 |
| 12.5 | 0.94800 | 0.03800 | 1.58 | 0.09050 | 0.09295 | 298.37 | 9502.21 |
| 13 | 0.95000 | 0.04000 | 1.67 | 0.09350 | 0.09595 | 308.00 | 9808.90 |
| 13.5 | 0.95200 | 0.04200 | 1.75 | 0.09600 | 0.09845 | 316.02 | 10064.47 |
| 14 | 0.95500 | 0.04500 | 1.88 | 0.09830 | 0.10075 | 323.41 | 10299.60 |
| 14.5 | 0.95750 | 0.04750 | 1.98 | 0.00070 | 0.10315 | 331.11 | 10544.95 |
| 15 | 0.96000 | 0.05000 | 2.08 | 0.00300 | 0.10545 | 338.49 | 10780.08 |
| 15.5 | 0.96250 | 0.05250 | 2.19 | 0.00520 | 0.10765 | 345.56 | 11004.98 |
| 16 | 0.96500 | 0.05500 | 2.29 | 0.00720 | 0.10965 | 351.98 | 11209.44 |
| 17 | 0.96550 | 0.05550 | 2.31 | 0.09250 | 0.09495 | 304.79 | 9706.67 |
| 17.5 | 0.96600 | 0.05600 | 2.33 | 0.09420 | 0.09665 | 310.25 | 9880.46 |
| 18 | 0.96600 | 0.05600 | 2.33 | 0.09650 | 0.09895 | 317.63 | 10115.59 |
| 18.5 | 0.96650 | 0.05650 | 2.35 | 0.09790 | 0.10035 | 322.12 | 10258.71 |
| 19 | 0.96675 | 0.05675 | 2.36 | 0.09930 | 0.10175 | 326.62 | 10401.83 |
| 20 | 0.96700 | 0.05700 | 2.38 | 0.09950 | 0.10195 | 327.26 | 10422.28 |
| 20.5 | 0.96775 | 0.05775 | 2.41 | 0.00400 | 0.10645 | 341.70 | 10882.31 |
| 21 | 0.96850 | 0.05850 | 2.44 | 0.00750 | 0.10995 | 352.94 | 11240.11 |
| 21.5 | 0.97150 | 0.06150 | 2.56 | 0.01210 | 0.11455 | 367.71 | 11710.37 |

| | | |
|---|---|---|
| Rate | 0.5 | mm/min |
| Diameter sample | 2.4 | in |
| Diameter sample | 0.20 | ft |
| Proving ring cal. | 3210.00 | lbs/in |
| Cross sec. Area | 0.0314 | ft2 |
| Vertical Load | 157 | lbs |
| Vertical Load | 71.21400209 | kg |
| Normal Stress | 5000 | psf |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 22 | 0.97500 | 0.06500 | 2.71 | 0.01550 | 0.11795 | 378.62 | 12057.95 |
| 23 | 0.98150 | 0.07150 | 2.98 | 0.02050 | 0.12295 | 394.67 | 12569.09 |
| 24 | 0.99000 | 0.08000 | 3.33 | 0.02550 | 0.12795 | 410.72 | 13080.24 |
| 24.5 | 0.99500 | 0.08500 | 3.54 | 0.02780 | 0.13025 | 418.10 | 13315.37 |
| 25 | 0.00050 | 0.09050 | 3.77 | 0.02980 | 0.13225 | 424.52 | 13519.82 |
| 25.5 | 0.00500 | 0.09500 | 3.96 | 0.03180 | 0.13425 | 430.94 | 13724.28 |
| 26 | 0.01000 | 0.10000 | 4.17 | 0.03420 | 0.13665 | 438.65 | 13969.63 |
| 26.5 | 0.01400 | 0.10400 | 4.33 | 0.03600 | 0.13845 | 444.42 | 14153.65 |
| 27 | 0.01800 | 0.10800 | 4.50 | 0.03800 | 0.14045 | 450.84 | 14358.11 |
| 28 | 0.02750 | 0.11750 | 4.90 | 0.04150 | 0.14395 | 462.08 | 14715.91 |
| 29 | 0.03700 | 0.12700 | 5.29 | 0.04500 | 0.14745 | 473.31 | 15073.71 |
| 29.5 | 0.04350 | 0.13350 | 5.56 | 0.04640 | 0.14885 | 477.81 | 15216.83 |
| 30 | 0.04800 | 0.13800 | 5.75 | 0.04770 | 0.15015 | 481.98 | 15349.73 |
| | | | | Shear Stress at Failure = | | | 15,350 |

Consolidated Undrained* Triaxial Compression Test
**with measurement of Pore Pressure**

| Client | MSE Technology Applications | Lab Ref | NA |
|---|---|---|---|
| Project | Beneficial Use of Red Mud and Phosphogypsum | Job | LAB01 141 |
| Borehole | NA | Sample | 3F-1 |

## Test Details

| | | | |
|---|---|---|---|
| **Standard** | ASTM D4767-04 | **Particle Density** | 2.70 Mg/m$^3$ (Assumed) |
| **Test Definition** | Consolidated Undrained | **Drainage location** | Bottom |
| **Sample Type** | Small disturbed sample | **Lab. Temperature** | 24.0 deg.C |
| **Sample Description** | 1 Part PGA to 4 Parts RMA compacted to approx 90 percent of dry max density at near optimum MC | | |
| **Variations from Procedure** | *Sample was accidentally tested under Consolidated Drained conditions | | |

## Specimen Details

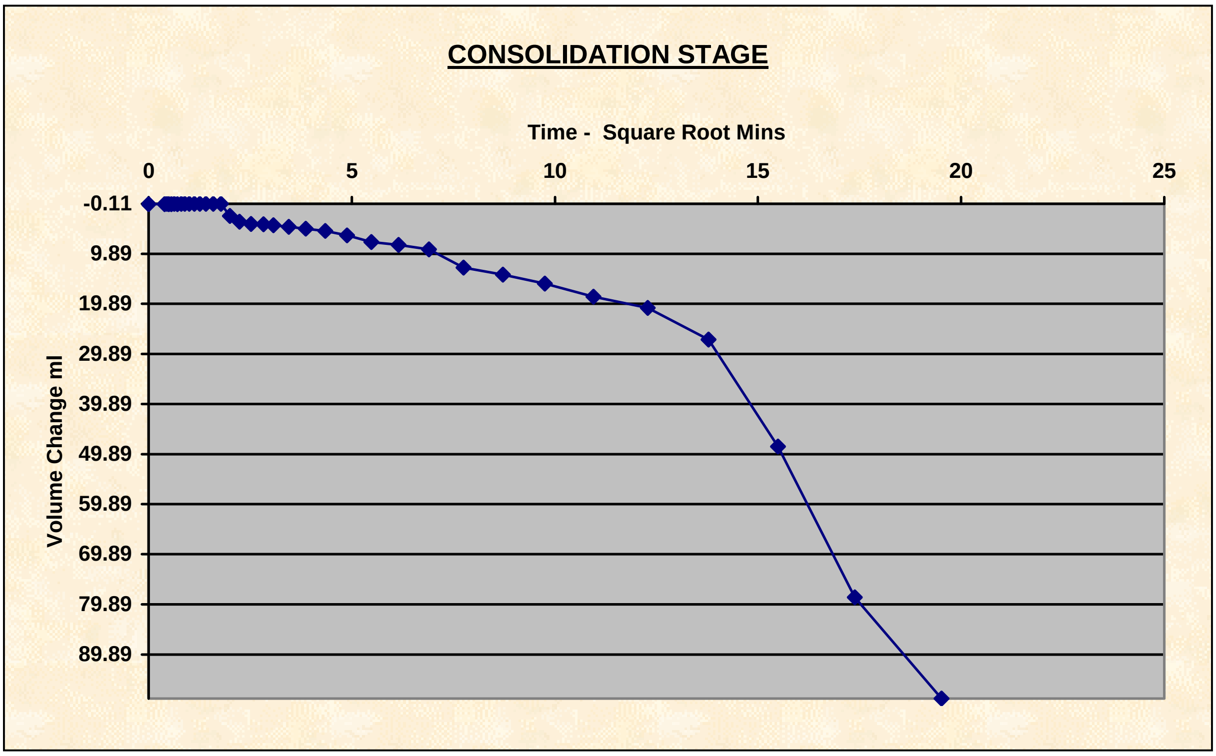
| | | | |
|---|---|---|---|
| **Specimen Reference** | B | **Description** | Red Mud and Phosphogypsum Composite |
| **Depth within Sample** | NA | **Orientation within Sample** | NA |
| **Initial Height** | 143.66 mm | **Initial Diameter** | 69.42 mm |
| **Preparation** | Soil was compacted in a 3" diameter by 5.5" long mold with a rubber membrane | **Moisture Content** | 34.6 % (trimmings: 31.6 %) |
| **Bulk Density** | 1.87 Mg/m$^3$ | **Membrane Thickness** | 0.41 mm |
| **Comments** | None | | |

## SATURATION STAGE

| | | | |
|---|---|---|---|
| **Saturation Method** | Cell/Back Pressure Increments | **Cell Increments** | 68.9kPa |
| **Final Cell Pressure** | 344.6kPa | **Δ Pore Pressure** | >68.9kPa |
| **Final Pore Pressure** | Greater than 1.0, sample considered saturated | | |

Consolidated Undrained* Triaxial Compression Test
**with measurement of Pore Pressure**

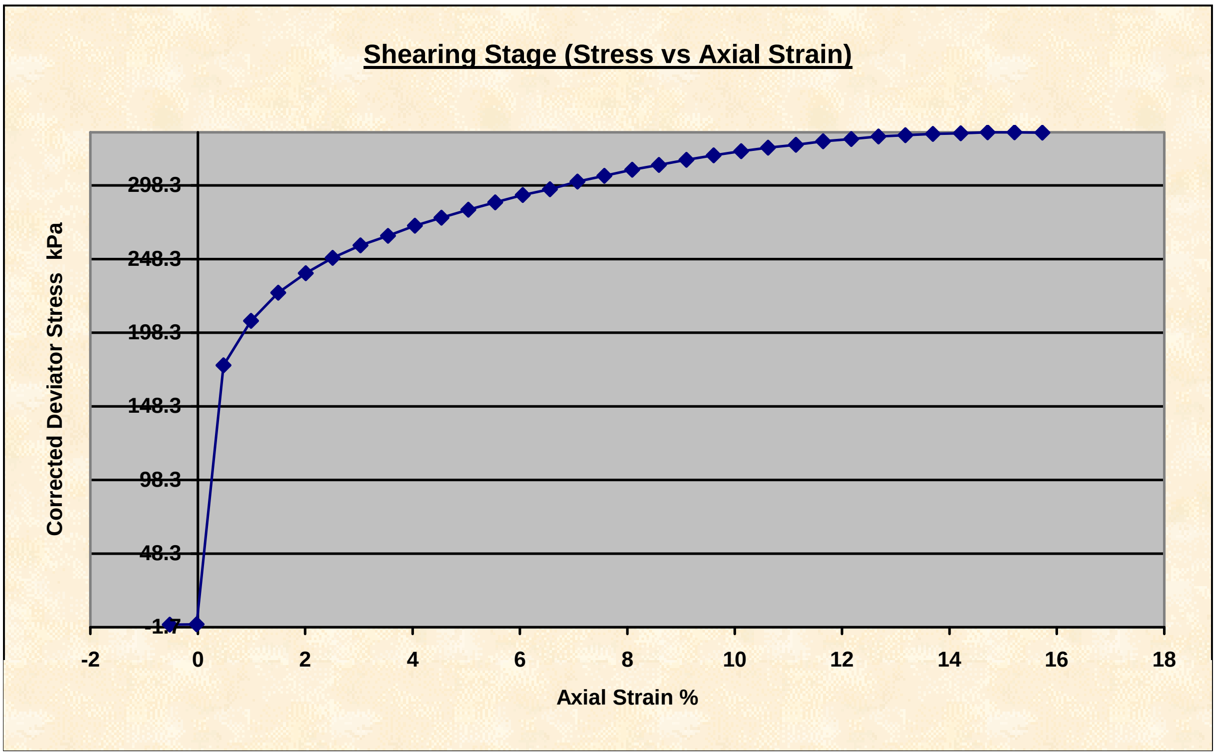
| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | NA |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 3F-1 |




| | | | |
|---|---|---|---|
| **Cell Pressure** | 267.2kPa | **Back Pressure** | 238.9kPa |
| **Effective Pressure** | 28.3kPa | **Final Pore Pressure** | 0.0 kPa |

Consolidated Undrained* Triaxial Compression Test
**with measurement of Pore Pressure**

| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | NA |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 3F-1 |



Consolidated Undrained* Triaxial Compression Test
**with measurement of Pore Pressure**

| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | NA |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 3F-1 |

## Shear Conditions

| | | | |
|---|---|---|---|
| **Rate of Axial Displacement** | 0.0558mm/min | **Cell Pressure** | 270.4kPa |
| **Initial Back Pressure** | 239.7kPa | **Effective Stress at Start of Stage** | 27.6kPa (4 psi) |

## Conditions at Failure

| | | | |
|---|---|---|---|
| **Failure Criterion** | Maximum Deviator Stress | | |
| **Pore Pressure** | 0.0kPa | **Minor Effective Principal Stress** | 264.5kPa |
| **Deviator Stress** | 334.3kPa | **Major Effective Principal Stress** | 598.8kPa |
| **Axial Strain** | 15.21% | **Effective Principal Stress Ratio** | 2.264 |
| **Deviator Stress Correction** | 1.8kPa | | |
| **Density** | 1.92 $Mg/m^3$ | **Moisture Content** | 32.3 % |

| | |
|---|---|
| Tested By and Date: | NAJ 7/28/08 |
| Checked By and Date: | KMP 7/28/08 |
| Approved By and Date: | NAJ 8/18/08 |


Mode of Failure

Consolidated Undrained* Triaxial Compression Test
**with measurement of Pore Pressure**

| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | None |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 3F-3 |

## Test Details

| | | | |
|---|---|---|---|
| **Standard** | ASTM D4767-04 | **Particle Density** | 2.70 Mg/m$^3$ (Assumed) |
| **Test Definition** | Consolidated Undrained | **Drainage location** | Bottom |
| **Sample Type** | Small disturbed sample | **Lab. Temperature** | 24.0 deg.C |
| **Sample Description** | 1 Part PGA to 4 Parts RMA compacted to approx 90 percent of dry max density at near optimum MC | | |
| **Variations from Procedure** | *Sample was accidentally tested under Consolidated Drained conditions | | |

## Specimen Details

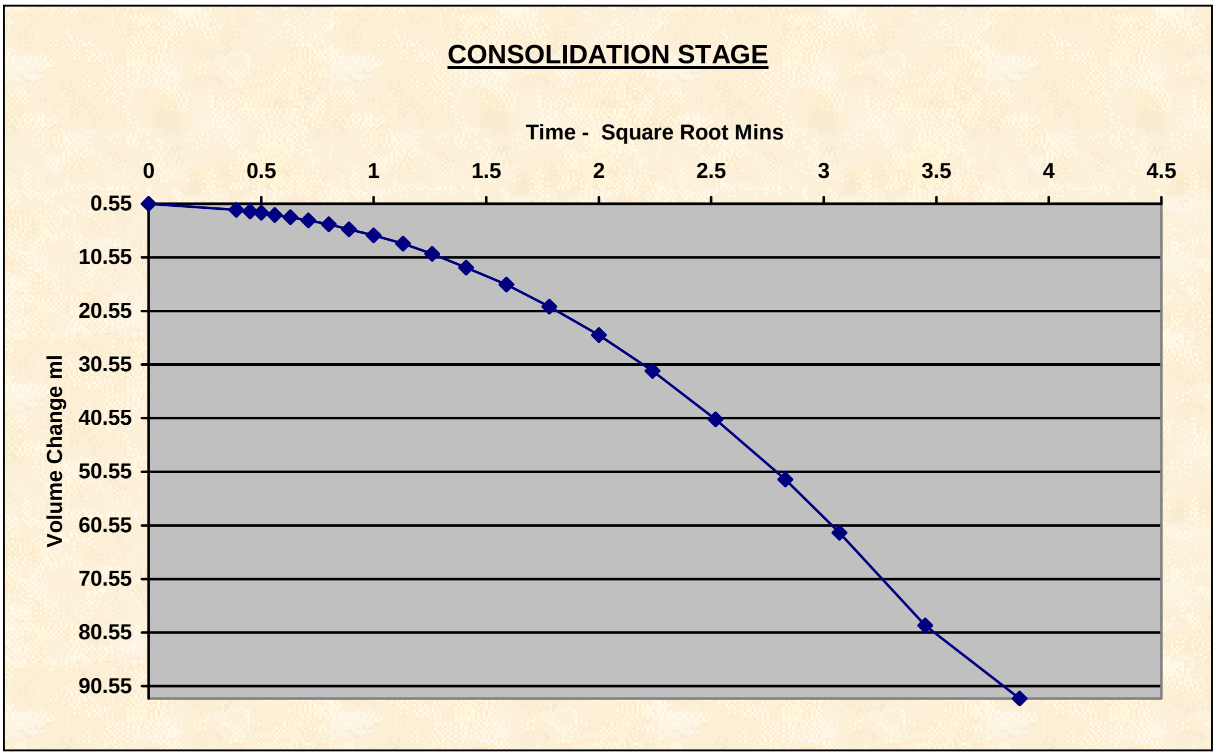
| | | | |
|---|---|---|---|
| **Specimen Reference** | B | **Description** | Red Mud and Phosphogypsum Composite |
| **Depth within Sample** | NA | **Orientation within Sample** | NA |
| **Initial Height** | 139.70 mm | **Initial Diameter** | 70.28 mm |
| **Preparation** | Soil was compacted in a 3" diameter by 5.5" long mold with a rubber membrane | **Moisture Content** | 34.2 % (trimmings: 31.6 %) |
| **Bulk Density** | 1.91 Mg/m$^3$ | **Membrane Thickness** | 0.41 mm |
| **Comments** | None | | |

## SATURATION STAGE

| | | | |
|---|---|---|---|
| **Saturation Method** | Cell/Back Pressure Increments | **Cell Increments** | 68.9kPa |
| **Final Cell Pressure** | 414.2kPa | **Δ Pore Pressure** | >68.9kPa |
| **Final Pore Pressure** | Greater than 1.0, sample considered saturated | | |

Consolidated Undrained* Triaxial Compression Test
**with measurement of Pore Pressure**

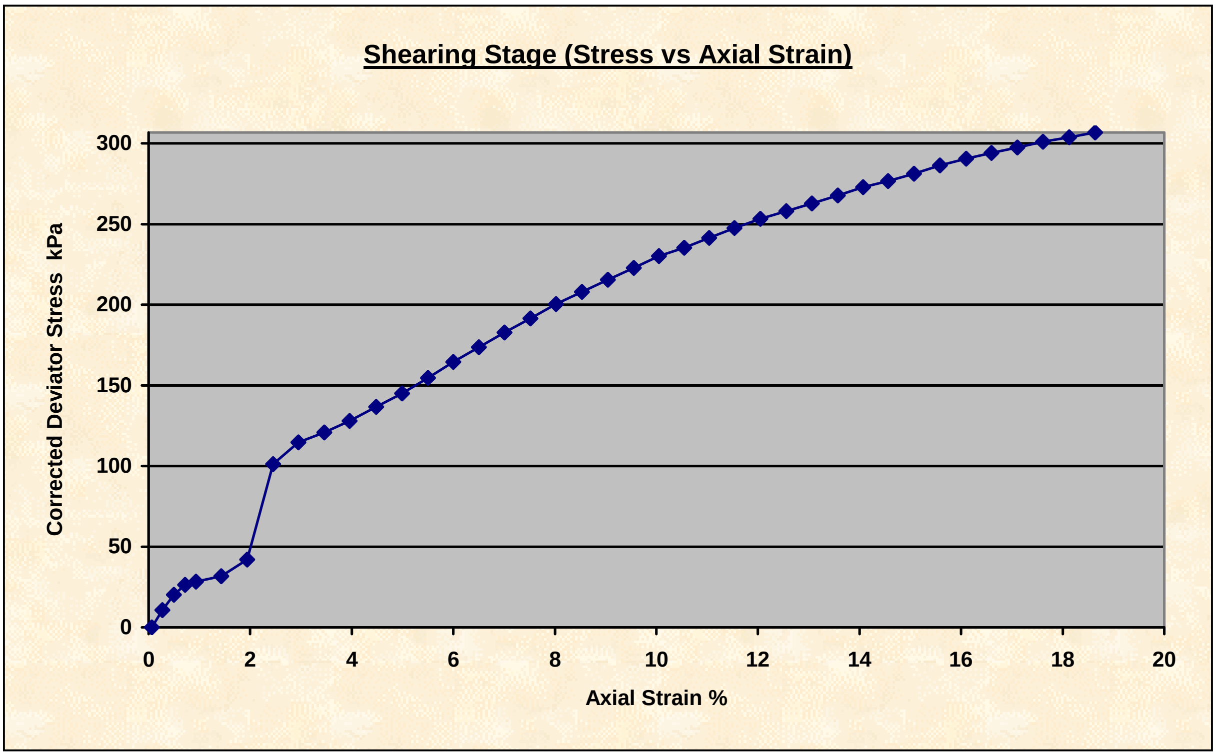
| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | None |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 3F-3 |




| | | | |
|---|---|---|---|
| **Cell Pressure** | 414.2kPa | **Back Pressure** | 371.2kPa |
| **Effective Pressure** | 43.0kPa | **Final Pore Pressure** | 0.0 kPa |

Consolidated Undrained* Triaxial Compression Test
**with measurement of Pore Pressure**

| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | None |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 3F-3 |



Consolidated Undrained* Triaxial Compression Test
**with measurement of Pore Pressure**

| | | | |
|---|---|---|---|
| **Client** | MSE Technology Applications | **Lab Ref** | None |
| **Project** | Beneficial Use of Red Mud and Phosphogypsum | **Job** | LAB01 141 |
| **Borehole** | NA | **Sample** | 3F-3 |

## Shear Conditions

| | | | |
|---|---|---|---|
| **Rate of Axial Displacement** | 0.0519mm/min | **Cell Pressure** | 413.6kPa |
| **Initial Back Pressure** | 372.23 kPa | **Effective Stress at Start of Stage** | 41.37kPa (6 psi) |

## Conditions at Failure

| | | | |
|---|---|---|---|
| **Failure Criterion** | Maximum Deviator Stress | | |
| **Pore Pressure** | 0.0kPa | **Minor Effective Principal Stress** | 414.2kPa |
| **Deviator Stress** | 281.3kPa | **Major Effective Principal Stress** | 695.5kPa |
| **Axial Strain** | 15.07% | **Effective Principal Stress Ratio** | 1.679 |
| **Deviator Stress Correction** | 1.8kPa | | |
| **Density** | 2.27 $Mg/m^3$ | **Moisture Content** | 33.5 % |

| | |
|---|---|
| Tested By and Date: | NAJ 8/1/08 |
| Checked By and Date: | KMP 8/1/08 |
| Approved By and Date: | NAJ 8/18/08 |