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# SOIL LABORATORY COMPACTION TECHNIQUES APPLIED TO ROLLER-COMPACTED CONCRETE

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16. ABSTRACT
A multiphase research program was designed and initiated by the Bureau to evaluate soil and concrete testing methods for use with RCC. This report documents phase I of the research program, which investigated the use of soil compaction techniques for RCC. The testing program evaluated effects of compactive effort and low plasticity fines content on an RCC mix currently used in Bureau research. Compressive strength and durability tests were performed on compacted test specimens. Standard Bureau soil and soil-cement laboratory testing procedures were modified for use in the program. Index unit weight and concrete consistency tests were performed for comparison purposes. Laboratory test data were evaluated using traditional soil and concrete theory. Test results indicate mix designs and preparation of specimens using laboratory compaction techniques provide an alternative for RCC. However, impact compaction testing should be limited to RCC mixes containing only hard, sound aggregate. Results of this study may be applied to soil-cement with gravel.

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October 1989

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## CONTENTS—Continued

## PURPOSE

Roller-compacted concrete (RCC) is a relatively new construction technique whereupon concrete is placed and compacted with equipment normally associated with soil-type compaction technology. RCC differs from conventional no-slump concrete principally by requiring a consistency of sufficient stiffness to support the mass of vibratory rollers, but having a sufficient volume of paste to fully consolidate under externally applied vibration. RCC has required the blending of concrete and soil technology which has produced two primary design methodologies in engineering practice, one based on classical concrete design and construction control techniques and the other based on soil compaction and construction control techniques.

Currently, classical concrete techniques are used by the Bureau of Reclamation, U.S. Army Corps of Engineers, and private industry for both mix design and construction control, while soil compaction techniques have been used for mix design and construction control of RCC by private industry [1].[1] Phase I of the testing program was developed to further investigate using soil compaction techniques with RCC and to make preliminary comparisons between concrete and soil compaction approaches. The testing program was designed to evaluate the effects of compactive effort and fines content on an RCC mix currently used in Bureau research. Bureau soil and soil-cement laboratory testing procedures were modified for this program. This report documents results of phase I of the testing program and presents conclusions derived from evaluating data obtained during testing.

## INTRODUCTION

A laboratory testing program was designed by the Bureau's Geotechnical Services Branch (Research and Laboratory Services Division) to investigate use of soil compaction techniques with RCC. This program is phase I of a multistage research program designed to evaluate soil and concrete testing methods for use with RCC. The effects of compactive effort and fines (material passing the U.S.A. Standard series No. 200 sieve) content were evaluated for the coarse-grained material.

Compressive strength and durability tests were performed on compacted test specimens. An RCC mix design currently used in a concrete technology-based RCC research program in the Bureau's Concrete and Structural Branch was used as the basis for mix designs in this investigation. The Bureau's soil and soil-cement laboratory testing procedures were modified for use in the program. Index unit weight and concrete consistency tests were performed for comparison purposes. Results of this study may be applied to soil-cement with gravel.

This report summarizes results of the laboratory testing program, testing procedures, and equipment modifications.

## SUMMARY

A laboratory testing program was initiated to investigate the use of soil compaction techniques with RCC. This is phase I of a multistage research program designed to compare soil and concrete testing methods for use with RCC. The effects of varied compactive efforts and the addition of low plasticity fines (Bonny loess) to RCC mixes were evaluated. An RCC mix, containing 300 $lbm/yd^3$ cementitious materials (50% fly ash and 50% cement) or 8.3 percent cementitious materials by dry mass of aggregate — currently used for a concrete technology-based RCC research program — was used as the basis for the mix designs in this testing program. Bureau of Reclamation soil and soil-cement laboratory test procedures were modified for use in the program. Results of this study also can be applied to coarse-grained soil-cement.

The testing program consisted of laboratory compaction testing of aggregate mixes and RCC mixes at four compactive efforts:

- 7.2 ft-lbf/$in^3$ (27 blows/lift)
- 13.3 ft-lbf/$in^3$ (50 blows/lift)
- 21.2 ft-lbf/$in^3$ (80 blows/lift)
- 32.4 ft-lbf/$in^3$ (122 blows/lift)

The mixes contained three fines contents (0,10, and 20%, by volume of aggregate).

Zero to two percent fines (minus No. 200 material) is standard for current Bureau RCC mixes. The mixes containing only aggregate or aggregate and fines were prepared by deleting cementitious materials and water reducing admixture, but keeping other constituents in proportion to the original mix design. When fines were used in the RCC mix, computations for the percentage of fines were based on the volume of aggregate only. The fines replaced an equal volume of sand in the original mix.

Compressive strength and W-D and F-T (wet-dry and freeze-thaw) durability tests were performed on compacted specimens of RCC to evaluate the effect of different compactive efforts and fines contents on these properties. Gradation tests were performed on compacted specimens of RCC to determine the amount of gravel (coarse aggregate) breakdown

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[1] Numbers in brackets refer to the bibliography.

during the compaction process. In addition, index unit weight and concrete consistency tests were performed for comparison.

For this testing program, test specimens were compacted in 6-inch-diameter by 12-inch-high modified concrete split steel molds ("Coulee" molds) using a 10.0-lbm sector-faced rammer dropped from a height of 18 inches. It was necessary to make several modifications to the automatic tamper to accommodate the 12-inch-high molds.

The compaction test specimens were compacted in the mold in six lifts, each approximately 2 inches thick after compaction, with a designated number of blows per lift. Because of cement hydration, ovendry moisture content determinations provided erratic test results. Therefore, the design moisture content (by dry batch mass) was used to calculate the dry unit weight of each specimen. For each compaction test, at least five compacted specimens were obtained, and the moisture contents versus corresponding dry unit weights were plotted. The peak of the compaction curve defined the maximum dry unit weight and optimum moisture content. Maximum dry unit weights and optimum moisture contents were used as the basis for preparing compressive strength and durability test specimens.

Mixes for compressive strength test specimens were prepared at optimum moisture contents determined from the compaction test. The 6-inch-diameter by 12-inch-high test specimens were prepared in a similar manner as the laboratory compaction test specimens. Ten specimens were prepared at each energy level and fines content so that two specimens each could be tested at 7, 28, 90, 180, and 360 days after compaction.

The W-D and F-T durability tests were performed on compacted specimens to determine if modified soil-cement durability testing procedures could be applied to RCC testing. Mixes for durability test specimens were prepared at the optimum moisture contents determined from compaction tests. The 6-inch-diameter cylinders were prepared in a similar manner as those prepared for the compaction test. Following the initial curing phase, test specimens were cut 5.77 inches long to provide the same relationship of maximum aggregate size to surface area as provided by current soil-cement durability testing procedures. Four specimens were prepared at each fines content and compactive effort so that two specimens each could be used for W-D and F-T durability testing.

Gradation tests were performed on specimens of RCC compacted at each energy level and fines content to determine the percentage of coarse aggregate breakdown during the compaction process.

Wet method maximum index unit weight tests (with modifications to the testing procedure) were performed on RCC mixes prepared at the approximate optimum moisture contents determined for each compactive effort and fines content. The mixes were prepared at optimum moisture content because water could not be effectively added to the mixes with cementitious materials during vibration in the mold.

Concrete consistency tests were performed on mixes prepared at the approximate optimum moisture contents determined for each compactive effort and fines content. A Vebe vibratory table was not available for this portion of the testing program, so a mechanically driven vibratory table having adjustable eccentrics was calibrated to provide the same frequency and amplitude of vibration as a Vebe table.

## CONCLUSIONS

Several modifications to the automatic tamper were required to accommodate the 12-inch-high compaction molds.

When fines were used in the RCC mixes, material would stick to the mixer sides causing segregation. To eliminate this problem, it was necessary to stop the mixer, scrape the inside, and continue mixing for the remainder of the time.

Laboratory compaction tests showed that the maximum dry unit weight decreased and the optimum moisture content increased with the addition of fines. In addition, the maximum dry unit weight increased and the optimum moisture content decreased with an increase in compactive effort.

Compressive strength generally increased with increased compactive effort and generally decreased with the addition of fines. Murphy [2] has found that maximum unconfined compressive strength and flexural strength are achieved when the percent fines is between 3 and 7. Studies by Schrader, et al. [3], have shown nonplastic fines contents of 4 to 11 percent to be desirable. Additional studies on Bureau of Reclamation RCC mixes may indicate an optimum fines content between 0 and 10 percent.

Unconfined compressive strength generally decreased with an increased water-cementitious materials ratio, which follows traditional concrete theory for fully compacted concrete [4]. However, there is no way to determine if decreases in strength can be totally attributed to higher water-cementitious materials ratios or to lower compactive efforts applied to the RCC specimens prepared at higher water-cementitious materials ratios.

The 90-, 180-, and 360-day compressive strength test results were somewhat erratic, with the specimens compacted to the highest unit weights not consistently having the highest compressive strengths. This may be due to several factors, such as aggregate breakdown, not enough cement paste to fill voids in the drier mixes, and variations in water-cementitious materials ratio.

Durability test results were inconclusive indicating that this test may not be the most appropriate for coarse-grained material. The loss of large pieces of aggregate during durability testing caused inconsistent test results. Small mass losses were obtained for all RCC durability test specimens, including specimens having lower compressive strengths.

Results of gradation tests on all compacted materials showed some gravel breakdown. High percentages of gravel mass loss occurred when 80 and 122 blows per lift were used for compaction. There was a minimal increase in gravel mass loss between compaction at 27 and 50 blows per lift. As expected, the highest percentage of gravel mass loss occurred in the largest gravel size, since there could not be breakdown of larger particles to this size (¾ to 1-½ inches). Mass losses in the ¾ to 1-½-inch gravel ranged from 4 to 27 percent. The test results indicated that the total gravel mass loss (6 to 17%) increased with compactive effort and generally decreased with increased fines and moisture content; however, there was a significant increase in gravel mass loss between 50 and 80 blows per lift and a minimal increase in gravel mass loss between 27 and 50 blows per lift.

Maximum index unit weight test results on the RCC mixes were erratic indicating that this test may not be the most appropriate for the material. The cementitious materials and fines in the RCC mixes restricted free movement of added water and, consequently, affected proper consolidation of the specimens. The maximum index unit weight method is not appropriate for soils with more than about 12 to 15 percent fines. RCC mixes containing 10 or more percent fines plus cement and fly ash, which are prepared at low moisture contents, contain too high a percentage of fines to provide consistent and accurate data using the current vibratory compaction procedure.

Results of concrete consistency tests showed that a "mortar ring" (fig. 58) would not form in the mold for the drier mixes. With the addition of fines, "mortar rings" would only form at the higher water-cementitious materials ratios. Consistency test wet unit weights were somewhat erratic; however, the data did correlate closer to impact compaction test data than did maximum index unit weight test data. The consistency tests were performed using a mechanically driven vibratory table with adjustable eccentrics, instead of a concrete Vebe vibratory table, thus possibly producing nonstandard results. The dry mixes did not form the required "mortar ring." Voids were visible in the drier consistency test specimens making volume determinations by water replacement method difficult and possibly inaccurate.

Laboratory test data also were evaluated using traditional concrete theory. The theoretical zero air void unit weight (a wet unit weight) was calculated for each RCC mix design. These results showed that the highest theoretical percent compaction occurred when 27 and 50 blows per lift were applied to compaction test specimens. Maximum dry unit weights increased and optimum moisture contents decreased with increased compactive effort; however, at the higher compactive efforts (80 and 122 blows/lift), the RCC mixes were extremely dry, probably not forming enough cement paste to fill all voids. This indicates that theoretical percent compaction is lower even with the higher unit weights. At the highest fines content (20%), the theoretical percent compaction was substantially lower for mixes prepared at all moisture contents than those prepared at the lower fines contents (0 and 10%)

Results of the testing program indicate that impact compaction testing should be limited to RCC mixes containing only hard, sound aggregate. The compactive effort selected for testing should be low enough to minimize gravel breakdown yet high enough to provide adequate compaction. As aggregate breaks down, material properties change and fractured surfaces may not get coated with cement paste, which may be reflected in lower compressive strengths and higher durability losses. Compaction at the lowest energy level (27 blows/lift) was too low as voids were observed over the entire surface of test specimens. Increased fines content and increased moisture content reduce, but do not eliminate, gravel breakdown during impact compaction testing, thus increasing the desirability of fines in the mix design.

The optimum moisture content determined by laboratory impact compaction methods is dependent upon the aggregates, fines content, cementitious materials content, and compactive effort applied. Loss of strength occurs when the moisture content is dry of optimum. Loss of strength also occurs wet of optimum due to higher water-cementitious materials ratios. When selecting a compactive effort to determine optimum moisture content, consideration should be given to providing enough moisture to allow complete hydration and enough paste to fill the voids. Moisture content is defined as mass of water divided by dry mass of solids, expressed as a percentage. It is difficult to compare strengths of mixes prepared at different moisture contents because of variation in water-cementitious materials ratio.

Based on all test results, the compactive effort of 13.3 ft-lbf/in$^3$ (50 blows/lift) appears to provide the best test specimens by impact compaction. This is the recommended compactive effort for future RCC impact compaction testing. A lower compactive effort than described by Yates and Reeves [1] was recommended by the Bureau of Reclamation because of increased gravel breakdown at higher compactive efforts.

The test results indicate that mix designs and preparation of specimens using laboratory compaction techniques provide a viable alternative for RCC mixes containing hard, sound aggregate. This conclusion also is supported by studies performed by Tayabji and Okamoto [5].

Accurate ovendried moisture contents cannot be determined directly for RCC mixes because of cement hydration and large sample sizes. To obtain a representative moisture sample, an extremely large sample of RCC is required. Because of the large sample size, the ovendrying process takes a long period of time during which the cement continues to hydrate and moisture becomes trapped in the RCC mixture. Therefore, it is necessary to use calculated moisture contents based on the mix design. Further investigations should consider use of wet unit weights for evaluating RCC.

Further study should be given to developing a vibratory (consolidation) test for use with coarse-grained material as impact compaction breaks down the coarse particles, thus changing properties of the RCC mixture. A vibratory-type test better simulates field placement condition because RCC is compacted in the field with a vibratory roller. A vibration test is also needed for coarse-grained soil-cement as soil-cement mixtures are becoming coarser and vibratory compaction methods have been used in recent soil-cement construction.

## DESCRIPTION OF TESTING PROGRAM

The testing program consisted of laboratory impact compaction tests using 4 different compactive efforts (7.2, 13.3, 21.2, and 32.4 ft-lbf/in$^3$) on aggregate mixes and on RCC mixes containing 3 fines contents (0, 10, and 20%, by volume of aggregate). Zero to two percent fines (minus No. 200 material) is standard for current Bureau RCC mixes. Standard impact compaction tests for soil are not appropriate for and were not performed on the aggregate mixes containing 0 percent fines. Compressive strength, and wet-dry (W-D) and freeze-thaw (F-T) durability tests were performed on compacted specimens to evaluate the effects of different compactive efforts and fines contents. Gradation tests were performed on RCC specimens compacted at each energy level and fines content to determine the amount of coarse aggregate breakdown occurring during the compaction process. Additionally, index unit weight and concrete consistency tests were performed for comparison purposes.

An RCC mix design currently used for a concrete technology-based RCC research program was used as the basis for designing all mixes used in this program. Figure 1 illustrates the work accomplished under this testing program.

A 300-lbm/yd$^3$ cementitious material (50% fly ash and 50% cement) RCC mix — without fines — was used as the basis for designing all mixes; this original mix design is shown in table 1. The result is a cementitious materials content of 8.3 percent by dry mass of soil (aggregate). Appendix A defines terms used in this report.

To evaluate the effect of adding low plasticity fines to RCC, mixes were designed with 10 and 20 percent fines (Bonny loess) by volume. The fines were substituted for an equal volume of sand in the mix. Figure B-1 shows the gradation of the 3 RCC mixes (containing 0, 10, and 20% fines). These mix designs still contained 8.3 percent cementitious materials (50% fly ash and 50% cement) by dry mass of fines and aggregate.

Laboratory impact compaction tests were performed using 4 energy levels (efforts) on RCC mixes containing 0, 10, and 20 percent fines and on aggregate mixes containing 10 and 20 percent fines. Test specimens were compacted in 6-inch-diameter by 12-inch-high split steel molds using a 10.0-lbm sector-faced rammer dropped from a height of 18 inches. The material was placed and compacted in the mold in 6 lifts (layers) — in thicknesses of approximately 2 inches per compacted lift (layer). Maximum aggregate size was 1-½ inches. The 4 energy levels selected for testing were designated as: USBR 27, 50, 80, and 122.

- USBR 27 resulted in a compactive effort of 7.2 ft-lbf/in$^3$ (27 blows/lift) which is about the same compactive effort applied using ASTM: D 698 [6].
- USBR 50 resulted in a compactive effort of 13.3 ft-lbf/in$^3$ (50 blows/lift) which is about the same compactive effort applied in TEX method Tex-113-E — the laboratory compaction procedure used by the Texas State Department of Highways and Public Transportation Materials and Tests Division [7].

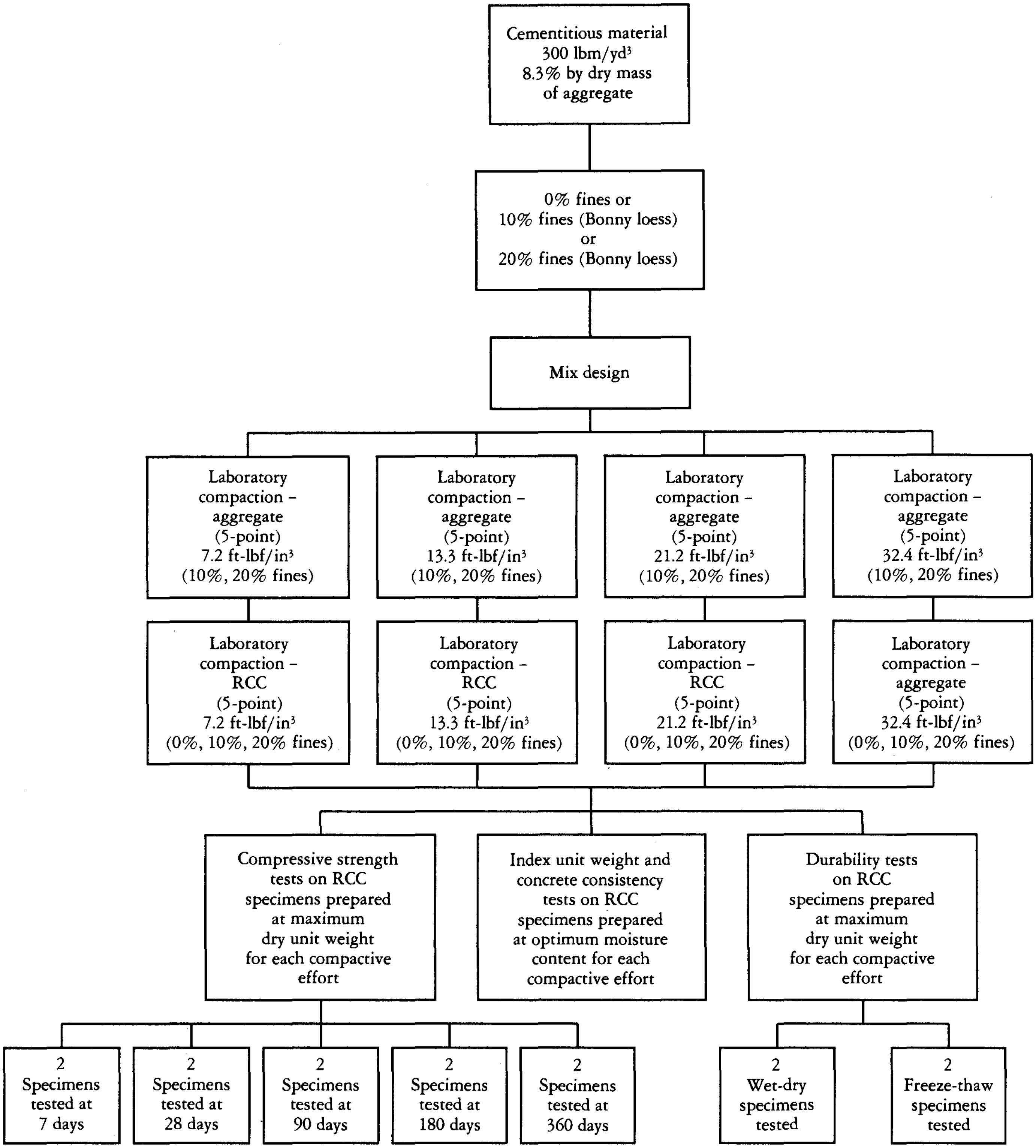


Figure 1.–The flow chart represents phase I of the research program.

Table 1.–Original roller-compacted concrete mix design — quantities per cubic yard.

| Mix ingredients | Size of material | Mass, lbm | Volume, ft³ |
|---|---|---|---|
| Coarse aggregate, | No. 4 to ⅜ in | 670 | 4.11 |
| (SSD—saturated | ⅜ to ¾ in | 910 | 5.55 |
| surface dry) | ¾ to 1-½ in | 1,100 | 6.69 |
| Sand (SSD) | | 952 | 5.77 |
| Cement | | 150 | 0.76 |
| Fly ash | | 150 | 1.07 |
| Water | | 164.5 | 2.64 |
| WRA (water reducing admixture) | | 354 mL | |
| Total solid volume | | | 26.59 |

Water-cementitious materials ratio equals 0.55

- USBR 122 resulted in a compactive effort of 32.4 ft-lbf/in³ (122 blows/lift) which is about the same compactive effort applied in ASTM: D 1557 [6].
- USBR 80 resulted in a compactive effort of 21.2 ft-lbf/in³ (80 blows/lift), and was selected as an intermediate energy level between energy levels applied by USBR 50 and 122.

The compactive efforts are summarized in table 2 and on figure 2. The sequence of testing for each mix is shown on figure 1.

Compaction testing was performed at each compactive effort for each mix, except for the aggregate mix containing 0-percent fines.

The optimum moisture content and maximum dry unit weight of each mix were determined for each compactive effort.

Compressive strength and W-D and F-T durability test specimens were compacted for each RCC mix at optimum moisture content and within ± 0.5 percent of maximum dry unit weight for each energy level.

Gradation tests were performed on the gravel portion of each RCC mix prior to mixing, and again after compaction and washing on the No. 4 sieve, to determine the percent of gravel breakdown due to compaction. The RCC mix gradation tests were performed on specimens compacted at optimum moisture content for each energy level.

Index unit weight and concrete consistency tests were performed on each RCC mix prepared at optimum moisture content for each energy level.

## MATERIALS

### Aggregate

Aggregate for this study was obtained from two Clear Creek, Colorado, aggregate sources. Sample No. M-3864 was obtained from Brannan Sand and Gravel Company, pit No. 10, located in Denver, Colorado; and sample No. M-7727 was obtained from Mobile Pre-Mix Crane Pit, located in Golden, Colorado. The aggregate was processed by the manufacturers into 4 sizes: sand, No. 4 to ⅜-inch gravel; ⅜- to ¾-inch gravel; and ¾- to 1-½-inch gravel.

Most testing was performed using aggregate from sample No. M-3864, except that the ¾- to 1-½-inch gravel portion of mixes containing 20 percent fines came from sample No. M-7727. Material from sample No. M-7727 was used when material from sample No. M-3864 was depleted. Coarse aggregate (gravel) from both sources was composed primarily of granite and gneiss. Results of petrographic analyses are included in appendix B. Aggregate from sample No. M-7727 had slightly more fractured surfaces than that from sample No. M-3864; however, this should not have significantly affected laboratory test data. Specific gravity and absorption test results for each gravel size are summarized in table 3.

The sand, angular to subangular in shape, was composed of the same rock types as the gravel. Specific gravity and absorption of the sand were 2.64 and 0.74 percent, respectively.

### Fines (Bonny Loess)

To evaluate the effect of adding low plasticity fines to RCC, mixes containing 10 and 20 percent natural fines (by volume) were prepared and tested. Bonny loess, sample No. 23J-4 (obtained near Bonny Reservoir in eastern Colorado) was used as fines for this investigation program. Laboratory testing on the Bonny loess to determine physical properties consisted of:

- gradation analyses,
- Atterberg limits,
- specific gravity, and
- laboratory compaction.

Tests were performed in accordance with procedures described in the *Earth Manual* [8]. Gradation analyses, Atterberg limits, and specific gravity tests were performed on eight specimens from sample No. 23J-4 to determine variability of the material.

The material was laboratory classified as silty clay (CL-ML) and silt (ML), containing 15 to 24 percent

Table 2.–Compactive effort summary — number of blows for 6-inch-diameter by 12-inch-high mold using a 10.0-lbm rammer and 18-inch drop.

| Test description | Compactive effort | | Number of blows required to provide specified compactive effort | |
|---|---|---|---|---|
| | $\frac{\text{ft-lbf}}{\text{in}^3}$ | $\frac{\text{ft-lbf}}{\text{ft}^3}$ | Blows per 2-in thick lift | Total number of blows |
| ASTM: D 698* | 7.2 | 12,375 | 27.1 | 163 |
| USBR 27 | 7.2 | 12,442 | 27.0 | 162 |
| USBR 50 | 13.3 | 22,982 | 50.0 | 300 |
| Tex-113-E | 13.3 | 22,982 | 50.1 | 301 |
| USBR 80 | 21.2 | 36,634 | 80.0 | 480 |
| USBR 122 | 32.4 | 55,987 | 122.0 | 732 |
| ASTM: D 1557† | 32.6 | 56,250 | 122.5 | 735 |

* ASTM: D 698, Standard Test Methods for Moisture-Density Relations of Soils and Soil-Aggregate Mixtures Using 5.5-lb (2.49-kg) Rammer and 12-in (305-mm) Drop.

† ASTM: D 1557, Standard Test Methods for Moisture-Density Relations of Soils and Soil-Aggregate Mixtures Using 10-lbm (4.54-kg) Rammer and 18-in (457-mm) Drop.

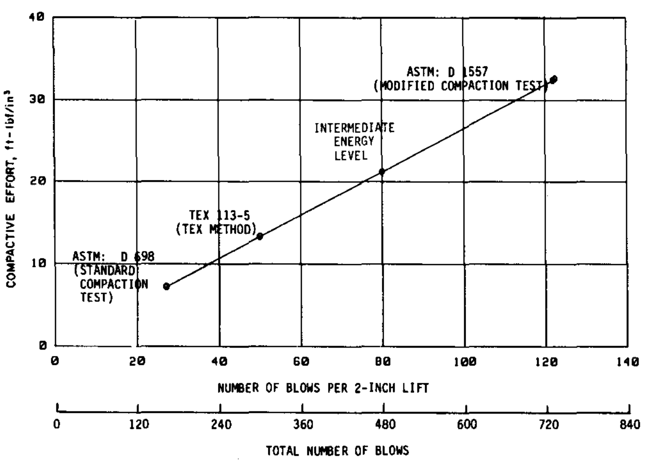


Figure 2.–Compactive effort versus number of blows for 6-inch-diameter by 12-inch-high mold, using a 10.0-lbm rammer and 18-inch drop.

sand. A summary plot of results of gradation tests performed on the 8 specimens is shown on figure B2. Figure B3 is a gradation test plot showing the average gradation of the 8 specimens tested. The LL (liquid limit) and PI (plasticity index) ranged from 22 to 27 percent and 2 to 7 percent, respectively, with an average LL of 25 percent and an average PI of 4 percent. Specific gravity of the material ranged from 2.60 to 2.65, with an average specific gravity of 2.63.

Based on results of physical properties tests, the material appeared quite uniform. Physical properties test results are summarized in table B1, and on figures B2 through B4. Values of PI versus LL are plotted on a plasticity chart shown on figure B4.

Table 3.–Summary of specific gravity and absorption test results for coarse aggregate.

| Size of material, inch | Sample No. | Bulk SSD specific gravity | Absorption, % |
|---|---|---|---|
| ¾ to 1-½ | M-3864 | 2.63 | 0.72 |
| ¾ to 1-½ | M-7727 | 2.63 | 0.75 |
| ⅜ to ¾ | M-3864 | 2.64 | 0.89 |
| No. 4 to ⅜ | M-3864 | 2.63 | 1.07 |

A laboratory compaction test performed on a specimen from the Bonny loess resulted in a maximum dry unit weight of 108 lbf/ft$^3$ at an optimum moisture content of 14.8 percent. Compaction test results are summarized in table B1 and on figure B5.

Results of a chemical analysis performed on a specimen of Bonny loess indicated the presence of less than 0.10 percent water soluble sulfate; therefore, type II cement was acceptable for use in the RCC mixtures containing Bonny loess.

A petrographic analysis was performed on a specimen of Bonny loess to determine mineralogical composition and estimated volume percentages — with emphasis on clay minerals. The material was composed predominantly of:

- quartz (45 to 50%),
- feldspar (10%),
- volcanic glass (10%),
- smectite (5 to 10%), and
- illite/mica (5 to 10%).

Appendix B has results of chemical and petrographic analyses.

### Cement

Type II low alkali cement (sample No. M-7120), manufactured by Ideal Basic Industries, Inc., located in Fort Collins, Colorado, was used in all RCC mixes. The cement had a specific gravity of 3.16.

### Fly Ash

Class F fly ash (sample No. M-7489), from the R. D. Nixon Powerplant, located in Fountain, Colorado, was used in all RCC mixes. The supplier of the fly ash was the Rocky Mountain Ash Company. The fly ash had a specific gravity of 2.23.

### Water Reducing Admixture

Protex PDA-25 WRA (water reducing admixture) agent was used in all RCC mixes.

### Water

Denver tapwater was used throughout the testing program.

## EQUIPMENT

### Compactor

A Rainhart series model 662 automatic tamper was used to compact test specimens. The Rainhart compactor is designed to compact specimens 4 to 6 inches in diameter and 6 inches high. The height of rammer drop is adjustable from 12 to 18 inches. Standard 5.5-lbm round and 10.0-lbm sector-faced rammers are available for use with the compactor.

For this testing program, the material was compacted in 6-inch-diameter by 12-inch-high modified concrete cylinder molds. The material was placed in the modified concrete cylinder molds in six approximately 2-inch-thick compacted lifts and compacted with a designated number of blows per lift using a 10.0-lbm sector-faced rammer dropped from a height of 18 inches.

Several modifications were made to the compactor to accommodate the 12-inch-high molds. The modified compactor is shown on figure 3. Appendix C shows details (including modifications) made to the compactor and the 6- by 12-inch compaction molds.

A new tamping rod was fabricated, moving the guide disk (see fig. 4) approximately 3 inches toward the tamper head, to prevent the guide disk from striking the grabber during compaction of the upper lifts of the specimen. The standard guide rods were lengthened to accommodate the lower path of the guide disk on the modified tamping rod. To obtain the additional travel distance for the guide disk, the bottom ends of the rear and the two side guide rods were cut perpendicular to the axis, drilled, and tapped; and 2-inch-long threaded short extension rods were fabricated and inserted into the ends of the guide rods to provide the required additional length. The front guide rod required a separate modification because additional clearance was required for installation and removal of the mold collar which was used during compaction of the top lift of the specimen. A 2-inch length was cut from the standard front guide rod and the end of the rod was drilled and tapped. A removable 4-inch-long threaded extension rod was inserted into the front guide rod. Figure 5 shows the 4-inch removable threaded extension rod. Figure 6 shows all 4 threaded extension rods.

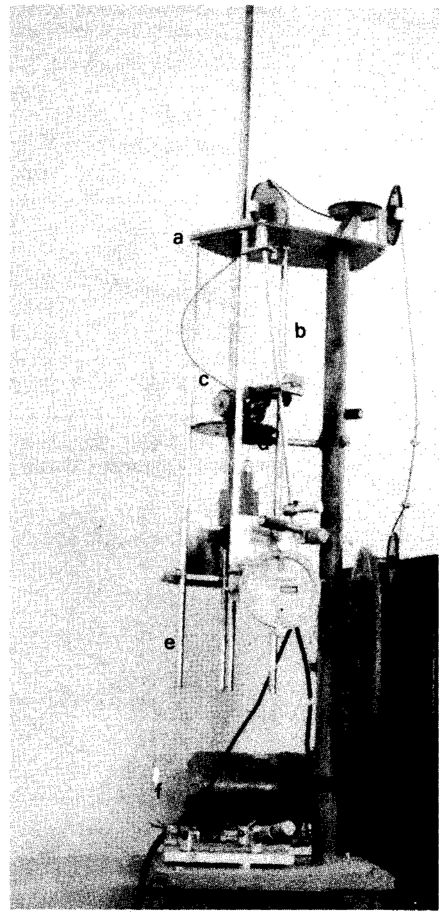

Figure 3.–Modified compactor used for roller-compacted concrete testing program. a) guide rod, b) grabber, c) guide disk, d) 10 lbm sector-faced rammer, e) threaded adaptors, f) cleat, and g) baseplate. P801-D-81408

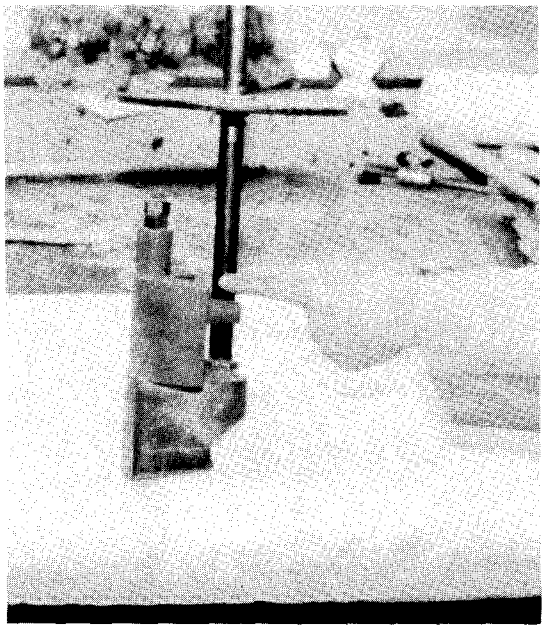

Figure 4.–Modified tamping rod used during test. The guide disk was moved approximately 3 inches toward the tamper head to prevent the guide disk from striking the grabber during compaction of the upper lifts of the specimen. P801-D-81402

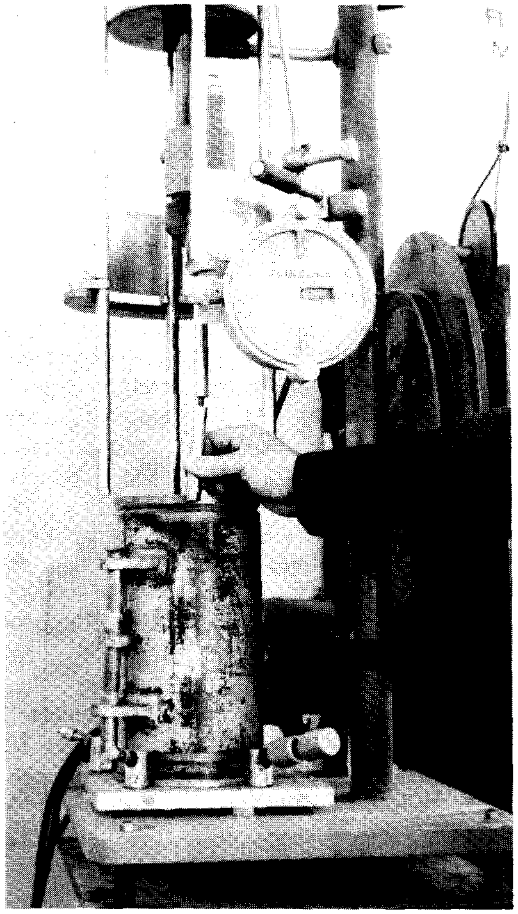

Figure 5.–View of the extension rod (4-inch threaded adapter) used to lengthen the standard front guide rod. P801-D-81403

The standard baseplate on the compactor has three cleats for securing the mold to the baseplate. During initial stages of testing, the mold moved throughout compaction of the upper lifts in the 12-inch-high mold. To stabilize the mold, an additional cleat was added to the baseplate.

## Molds

The molds selected for compacting the test specimens were modified concrete test cylinder molds, known as "Coulee" molds. These molds were used because of their rugged wrought steel design necessary for retaining shape and calibrated volume during compaction.

Several modifications were required to convert the concrete cylinder molds into compaction molds suitable for use with an automatic tamper. Because the locking lug system — for securing the bottom plate — would not rest evenly on the baseplate of the compactor, it was necessary to devise a new locking system. The locking lugs were removed, and six holes were drilled through the bottom plate and into the mold. The holes in the mold were tapped and screws were used to secure the bottom plate to the mold. The holes in the bottom plate were countersunk so the bottom plate would rest flush on the baseplate of the automatic tamper.

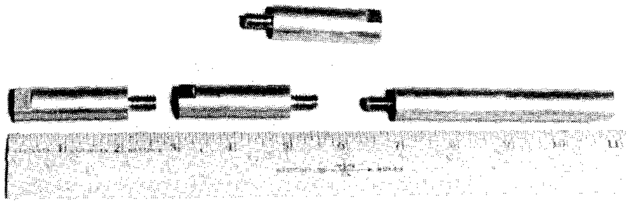

Figure 6.–Extension rods fabricated to provide additional travel distance for the guide disk. P801-D-81404

A mold centering guide was designed and fabricated to aid in centering the test cylinder compaction molds on the baseplate (fig. 7). After placing the mold on the baseplate, the mold centering guide was inserted into the top of the mold so the centering guide could be visually centered between the compactor guide rods, thus centering the mold on the baseplate. The mold centering guide saved considerable time over the previous trial-and-error method.

A collar was fabricated to aid compaction up to and slightly above the top of the compaction mold (fig. 8). Variation in the outside diameter of the tops of the molds required that the top outside 1-½ inches of each mold be machined to specified tolerances to fit the collar. Three bolts with wing nuts were used to hold the collar in place during compaction.

A modified concrete test cylinder mold is shown on figure 9. Figure 10 shows the modified concrete test cylinder compaction mold in comparison to the standard soil-cement and Bureau of Reclamation compaction molds.

The molds were calibrated using the water-filling method in accordance with designation USBR 1009.[2] Because of the new mold design, use of 1-½-inch aggregate, and high compactive efforts, frequent checks were made to verify mold volumes.

### Mixer

A Montgomery Ward and Co. model GIL-26471C electric mixer (3-¼ $ft^3$) was used for mixing the roller-compacted concrete.

## TESTING PROGRAM

### Batching

The mix design selected for testing was one currently used in the Bureau's Concrete and Structural Branch laboratory for a concrete technology-based RCC research program. Adjustments were made to the RCC mix design so that mixes of aggregate only, and aggregate having selected percentages of fines (0, 10, and 20%) could be tested. The mixes containing only aggregate and fines were computed by deleting cementitious materials and water reducing admixture, while keeping the aggregate and fines in proportion to the original mix design. When fines were used in the RCC mix, computation for the percentage of fines were based on the volume of aggregate only. The fines replaced an equal volume of sand in the mix. The sand in the RCC mixture was adjusted to account for the sand portion of the Bonny loess. The percentage of water required in the RCC mixture was computed based on the dry mass of the aggregate, fines, and cementitious materials.

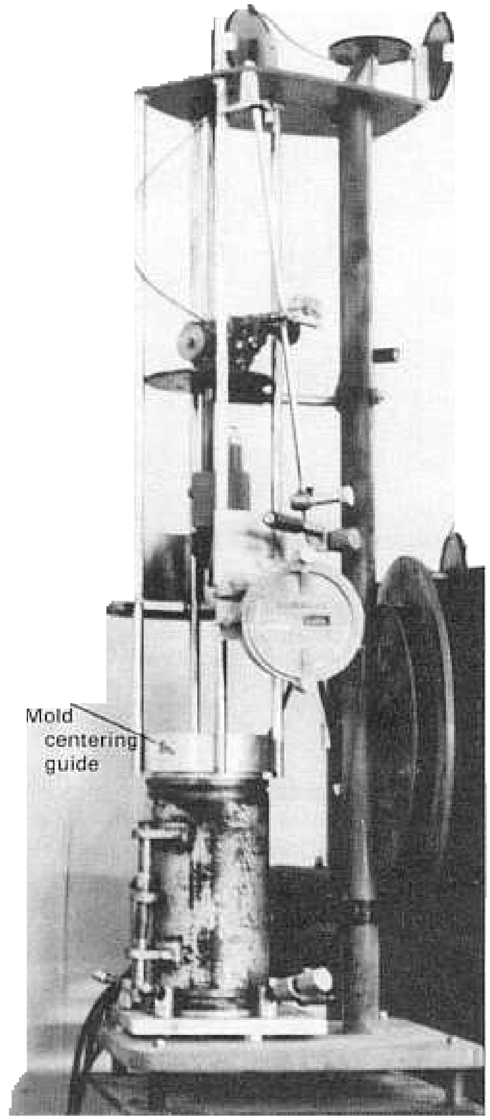


Figure 7.–Mold centering guide aids in centering compaction mold on the baseplate. P-801D-81405

Batch sizes of 0.3 and 0.6 $ft^3$ were used to provide material for either one or two specimens, respectively, as desired. Three types of mixes were required: (1) aggregate and fines only, (2) aggregate and cementitious materials without fines (original mix design), and (3) aggregate and cementitious materials with fines.

[2] USBR 1009 Testing Procedure, Procedure for Calibrating Compaction Molds, Bureau of Reclamation, Geotechnical Branch, Denver, Colorad.

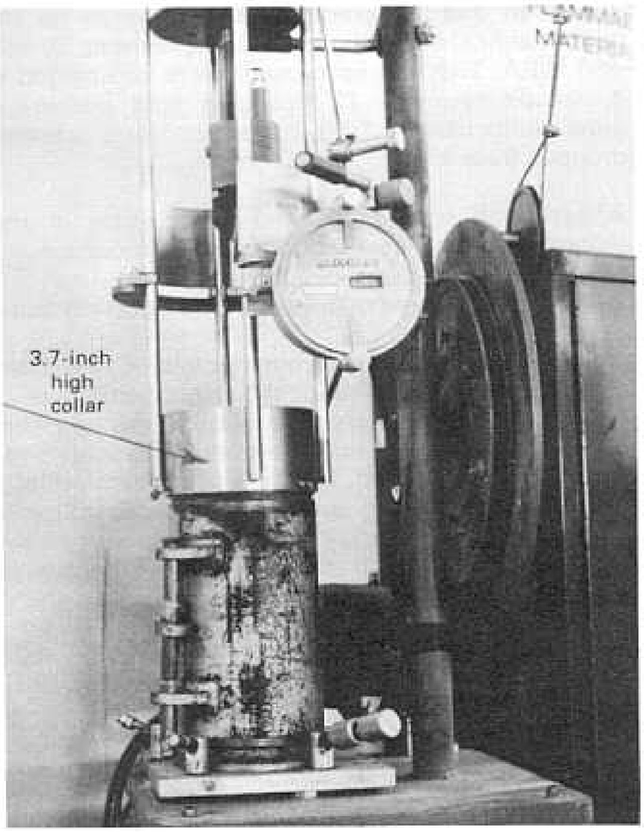


Figure 8.–Collar aids compaction up to and slightly above the top of the compaction mold. P801-D-81406

## Mixing

***Mixes of Aggregate With and Without Fines.***–Mixtures containing aggregate with or without fines were mixed by hand in a large pan. The desired quantity of water was sprinkled onto the materials and thoroughly mixed by hand. When fines were used, the moisture content of the fines was determined and that amount of water subtracted from the total amount of water required. After water was added, the mixtures were covered and allowed to stand for 10 minutes before compaction — to aid in dispersion and absorption of the water.

***Mixes of Aggregate and Cementitious Materials Without Fines.***–The mixing sequence selected was one currently used in the Bureau's concrete laboratory for RCC research. Each ingredient was measured individually. The aggregate and about one-half of the mix water were placed in the mixer and mixed for 1 minute. After 1 minute, the cement and fly ash (which were blended by hand), the remainder of the mix water, and the WRA were added to the mix; then the entire batch was mixed for 4 more minutes. The complete batch was dumped into a

Figure 9.–Modified concrete test cylinder mold used for roller-compacted concrete compaction tests. P801-D-81407

Soil-cement compaction mold

Bureau standard compaction mold

RCC compaction mold

Figure 10.–Modified roller-compacted concrete test cylinder compaction mold in comparison to the standard soil-cement and Bureau compaction molds. P801-D-81408

large pan and remixed with a shovel and trowel to minimize segregation before the material was placed in the compaction mold.

***Mixes of Aggregate and Cementitious Materials With Fines.***–The mixing sequence was essentially the same as mixing without fines, with a few exceptions. The moisture content of the fines was determined and that amount of water subtracted from the total amount of water required. The fines were mixed with the cement and fly ash immediately before putting them into the mixer. When fines were used, some of the material would stick to the mixer causing segregation. To eliminate this problem, mixing was stopped after 2 minutes, and the inside of the mixer was scraped and the mixing continued for the remaining 2 minutes. The mixer drum was scraped again after dumping the material into a large pan. The material was remixed with a shovel and trowel to minimize segregation before placing into the compaction mold.

When possible, 0.6-$ft^3$ batches of materials were mixed so that two specimens could be prepared from a single batch. Using larger batches, considerable time and labor were saved, and segregation appeared to be less. Careful planning was required to ensure that two specimens could be compacted within the 45-minute time limit specified between the addition of water to cement and completion of compaction. The mixtures were covered with damp towels after mixing and during compaction to help maintain a uniform moisture content and reduce the rate of temperature gain. On warm days, it was necessary to cool the mix water to reduce the rate of temperature gain.

***Laboratory Impact Compaction Tests on Aggregate Mixes With Fines.***–Laboratory compaction tests were performed at the selected energy levels (efforts) on aggregate mixes containing 10 and 20 percent fines. The blend of materials used for each test specimen met the gradation requirements for the specified RCC mix design, excluding cement, fly ash, and WRA. The test specimens were compacted in 6-inch-diameter by 12-inch-high split cylindrical steel molds using a 10.0-lbm sector-faced rammer, dropped from a height of 18 inches.

Appendix E has a detailed description of the laboratory impact compaction testing procedure.

Table 4 summarizes results of the compaction tests.

Figures 11 and 12 are summary plots of laboratory compaction curves showing the effect of compactive effort on maximum dry unit weight and optimum moisture content for aggregate mixtures with fines contents of 10 and 20 percent, respectively. Individual compaction curves are shown on figures D1 through D8. In some cases, the portion of the compaction curve on the wet side of optimum became quite flat.

***Laboratory Impact Compaction Tests on RCC Mixes.***–Laboratory compaction tests were performed at the selected energy levels (efforts) on RCC mixes containing 0, 10, and 20 percent fines. The required quantities of aggregate and fines (when required), cement, fly ash, water, and WRA were batched and mixed based on the RCC mix design and desired moisture content. The quantity of water was adjusted based on the absorption of the aggregate and moisture content of the fines (when required). The test specimens were compacted in 6-inch-diameter by 12-inch-high split steel molds using a 10.0-lbm sector-faced rammer, dropped from a height of 18 inches.

Figure 13 shows compaction of one RCC mix.

Because of cement hydration and large sample sizes, ovendry moisture content determinations provided erratic results. Therefore, the design moisture

Table 4. – Summary of laboratory compaction test results on mixes of aggregates and fines.

| Fines content % | Number of blows/lift | Compactive effort ft-lbf/$in^3$ | *Wet unit weight lbf/$ft^3$ | Maximum dry unit weight lbf/$ft^3$ | Ovendry optimum moisture content % |
|---|---|---|---|---|---|
| 10 | 27 | 7.2 | 150.9 | 142.6 | 5.8 |
| | 50 | 13.3 | 150.8 | 142.8 | 5.6 |
| | 80 | 21.2 | 151.8 | 144.2 | 5.3 |
| | 122 | 32.4 | 153.2 | 146.0 | 4.9 |
| 20 | 27 | 7.2 | 147.0 | 138.3 | 6.4 |
| | 50 | 13.3 | 149.0 | 140.0 | 6.4 |
| | 80 | 21.2 | 148.8 | 140.9 | 5.6 |
| | 122 | 32.4 | 149.7 | 142.6 | 5.0 |

* Wet unit weight at maximum dry unit weight

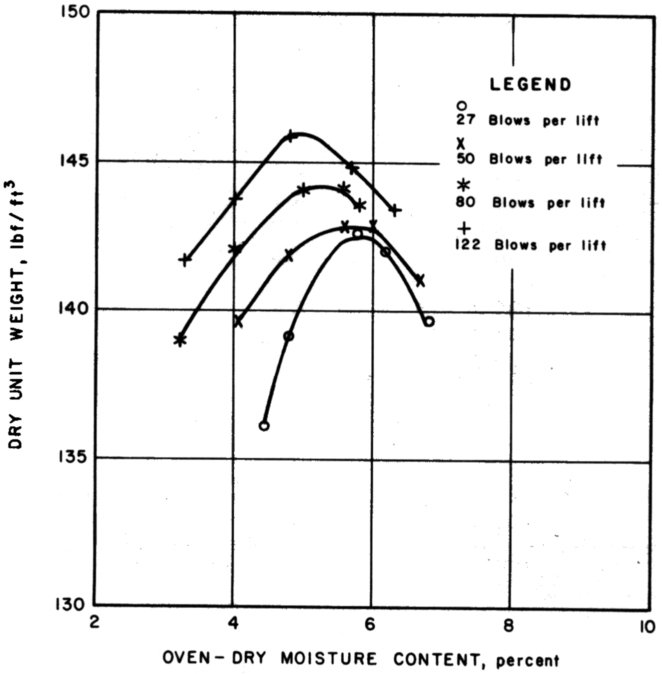


Figure 11.-Compaction curve of aggregate with 10 percent fines.

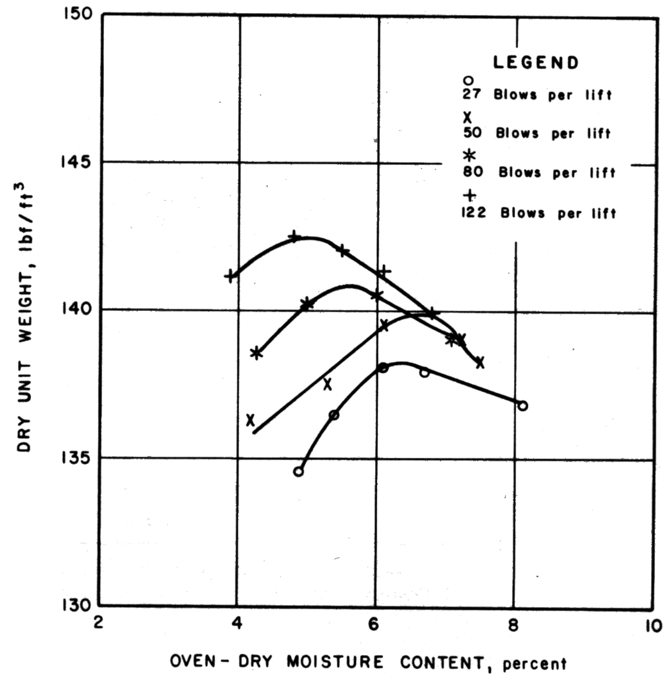


Figure 12.-Compaction curve of aggregate with 20 percent fines.

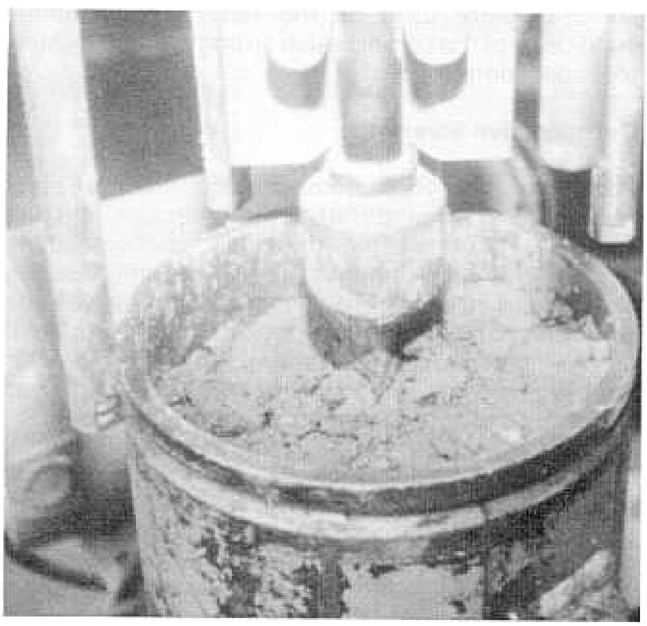

Figure 13.-View of roller-compacted concrete in a modified concrete mold during compaction with a 10.0-lbm sector-faced rammer.

content (by dry batch mass) was used to calculate the dry unit weight of each specimen. At least five compacted specimens were obtained, and the design moisture contents versus corresponding dry unit weights were plotted. If the peak of the curve was not well defined, additional specimens were prepared and compacted at appropriate moisture contents.

Appendix E has a detailed description of the laboratory impact compaction testing procedure.

Results of the compaction tests on the RCC mixes are summarized in table 5.

Laboratory compaction data for the RCC mixes are summarized in table D1 and on figures 14 through 22. In some cases, the portion of curve on the wet side of optimum became quite flat.

Maximum dry unit weight decreased and optimum moisture content increased with addition of fines.

- Figure 14 shows the relationship of maximum dry unit weight to number of blows per lift for the three fines contents.
- Figure 15 shows the relationship of optimum moisture content to number of blows per lift for the three fines contents.
- Figures 16 through 19 are summaries of compaction curves for the RCC mixes showing effect of fines content on maximum dry unit weight and optimum moisture content for each compactive effort. Maximum dry unit weight increased while optimum moisture content decreased with an increase in compactive effort.
- Figures 20 through 22 are summaries of RCC compaction curves for the RCC mixes showing the effect of compactive effort on maximum dry unit weight and optimum moisture content for each fines content.

Table 5. - Summary of laboratory compaction test results on roller-compacted concrete mixes.

| Fines content % | Number of blows/lift | Compactive effort ft-lbf/in³ | *Wet unit weight lbf/ft³ | Maximum dry unit weight lbf/ft³ | †Optimum moisture content % |
|---|---|---|---|---|---|
| 0 | 27 | 7.2 | 151.6 | 143.4 | 5.8 |
| | 50 | 13.3 | 152.6 | 145.2 | 5.1 |
| | 80 | 21.2 | 153.4 | 146.5 | 4.7 |
| | 122 | 32.4 | 153.6 | 146.8 | 4.6 |
| 10 | 27 | 7.2 | 149.4 | 139.8 | 6.9 |
| | 50 | 13.3 | 150.6 | 141.8 | 6.2 |
| | 80 | 21.2 | 149.8 | 142.7 | 5.0 |
| | 122 | 32.4 | 151.1 | 144.6 | 4.5 |
| 20 | 27 | 7.2 | 146.0 | 136.3 | 7.1 |
| | 50 | 13.3 | 146.7 | 137.9 | 6.4 |
| | 80 | 21.2 | 147.3 | 139.0 | 6.0 |
| | 122 | 32.4 | 148.6 | 141.3 | 5.2 |

* Wet unit weight at maximum dry unit weight.
† Individual moisture contents from mix design — not ovendry.

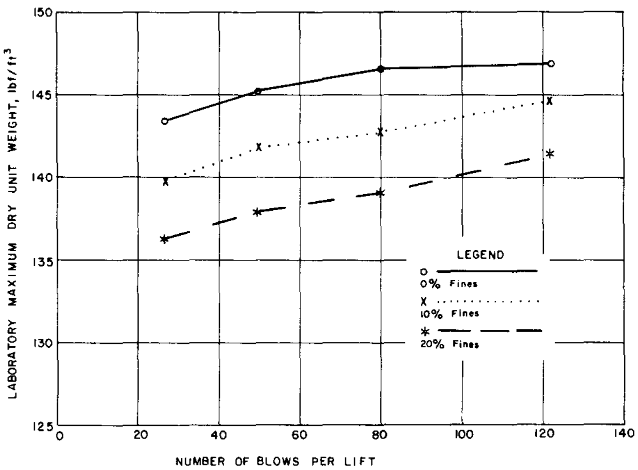


Figure 14.-Roller-compacted concrete — maximum dry unit weight versus number of blows per lift.

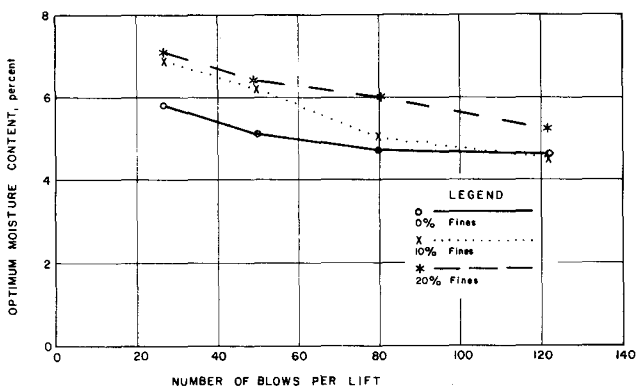


Figure 15.-Roller-compacted concrete — optimum moisture content versus number of blows per lift.

Individual compaction curves are shown on figures D9 through D20.

Maximum dry unit weights and optimum moisture contents were used as the basis for placement conditions of the compressive strength and durability test specimens.

## Compressive Strength

Mixes for the RCC compressive strength test specimens were prepared at the optimum moisture content determined from the laboratory compaction test. The 6-inch-diameter by 12-inch-high specimens were prepared in a similar manner as the laboratory compaction test specimens, except each layer was rodded 25 times with a 5/8-inch-diameter tamping rod to ensure that the material was uniformly distributed along the sides of the mold.

Specimens were compacted to within ±0.5 percent of maximum dry unit weight, as determined from the laboratory compaction test. Because of the coarse aggregate, the top surface of each specimen was usually rough after trimming. It was necessary to apply a thin cover [using a 3:1 (sand to cement) grout mix] to provide a relatively smooth, uniform, surface for the sulfur cap which was applied prior to compression testing.

Compacted specimens were cured in a fog room (100% humidity) at 73.4±3.0 °F for approximately 16 hours prior to removal from the compaction molds. After removal from the molds, the specimens were placed in the fog room for the remainder of the specified curing period. Ten specimens were prepared at each energy level and fines content so

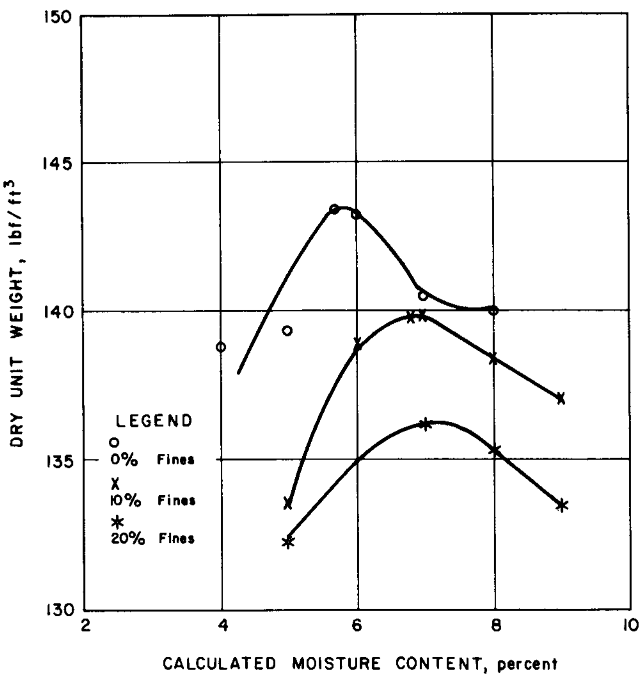


Figure 16.–Compaction curve for roller-compacted concrete (27 blows per lift — 0, 10, and 20% fines).

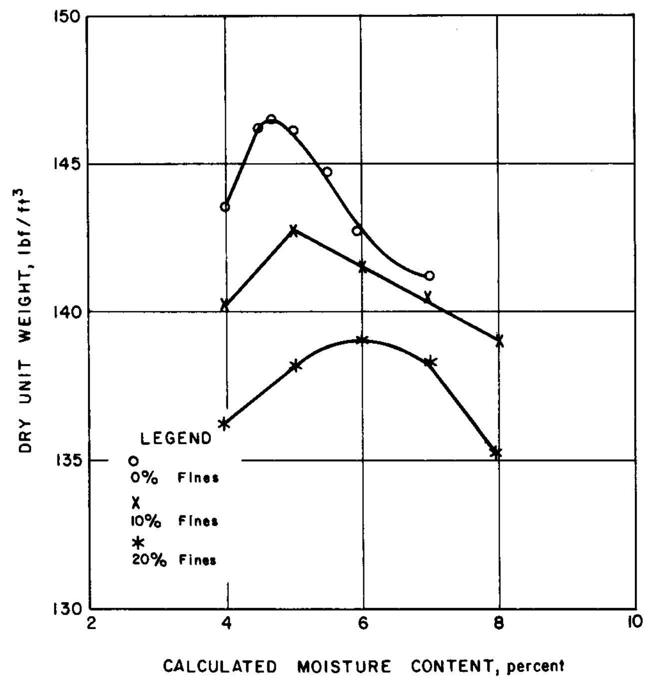


Figure 18.–Compaction curve for roller-compacted concrete (80 blows per lift — 0, 10, and 20% fines).

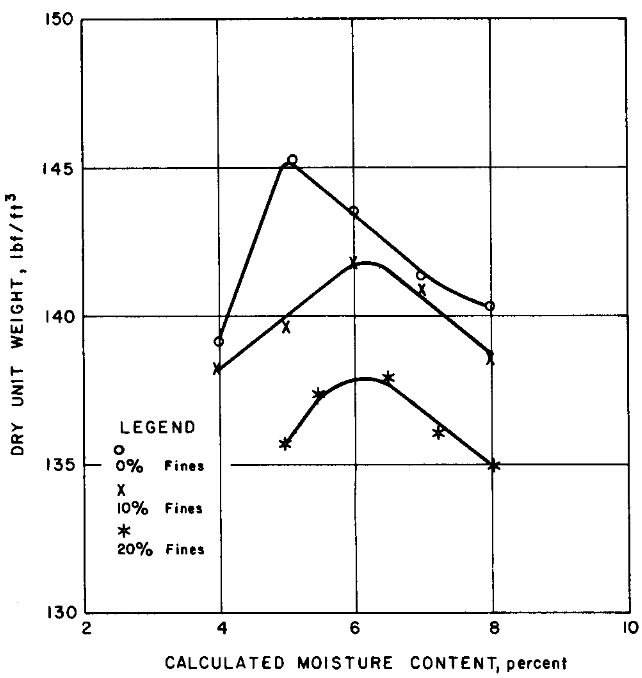


Figure 17.–Compaction curve for roller-compacted concrete (50 blows per lift — 0, 10, and 20% fines).

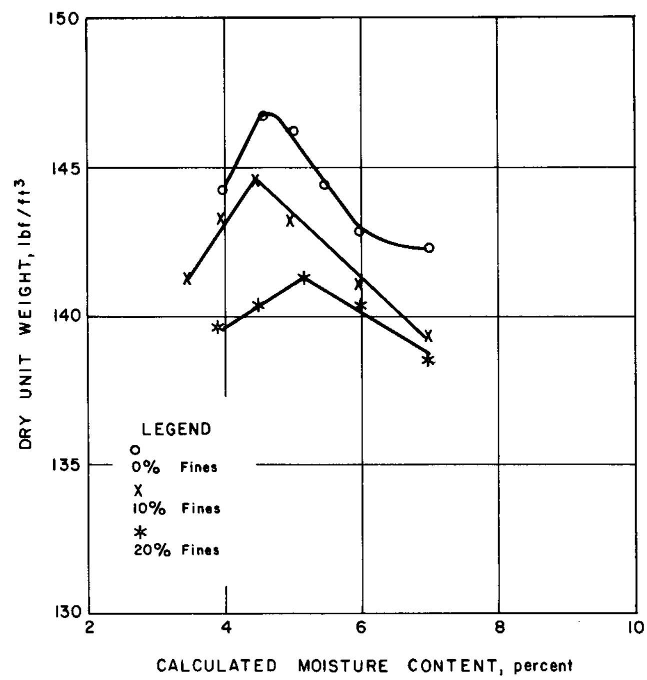


Figure 19.–Compaction curve for roller-compacted concrete (122 blows per lift — 0, 10, and 20% fines).

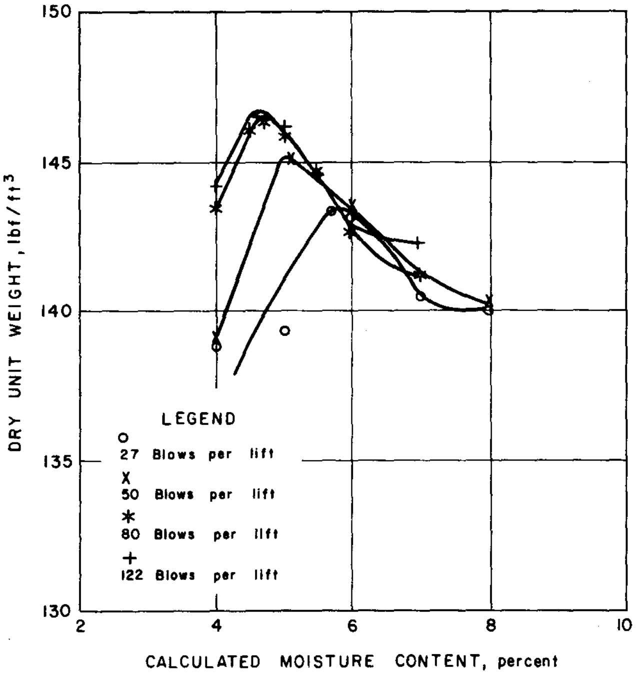


Figure 20.–Compaction curve for roller-compacted concrete (0% fines — 27, 50, 80, and 122 blows per lift).

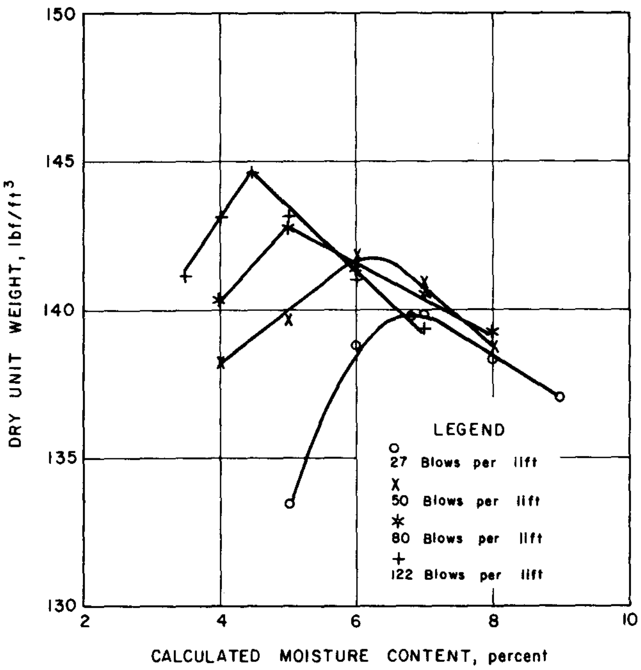


Figure 21.–Compaction curve for roller-compacted concrete (10% fines — 27, 50, 80, and 122 blows per lift).

that two specimens each could be tested at 7, 28, 90, 180, and 360 days after preparation.

- Figure 23 shows a typical pair of compressive strength test specimens ready for testing. The test specimens were loaded in compression to failure in accordance with the *Concrete Manual*, designation 33 Compressive Strength [9].

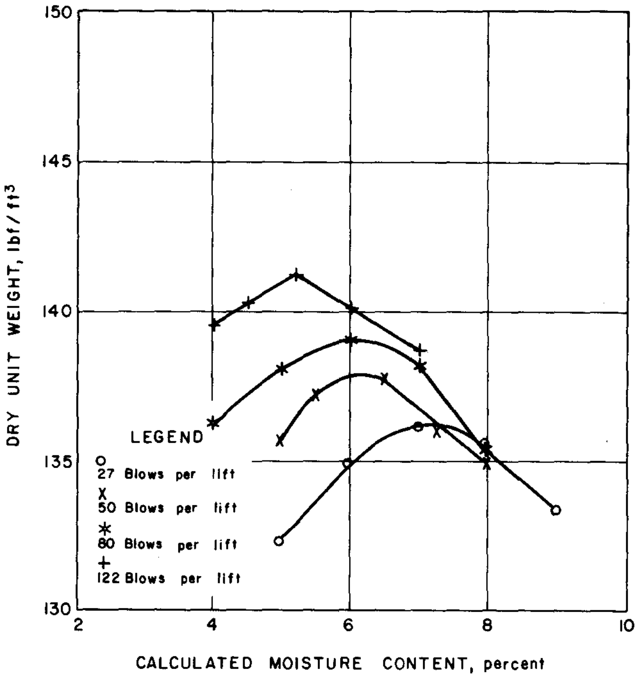


Figure 22.–Compaction curve for roller-compacted concrete (20% fines — 27, 50, 80, and 122 blows per lift).

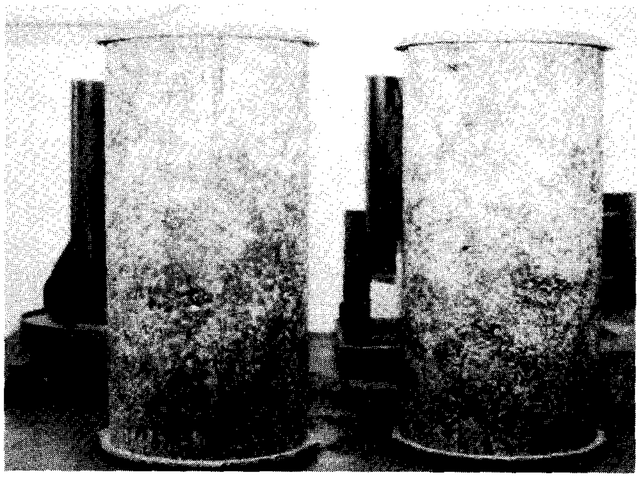

Figure 23.–Typical pair of roller-compacted concrete specimens prepared for compressive strength testing. P801-D-81410

- Figure 24 shows an RCC specimen during compression testing.
- Figure 25 is a closeup of a specimen after failure.

Appendix E has a detailed description of the compressive strength testing procedure used on the RCC specimens.

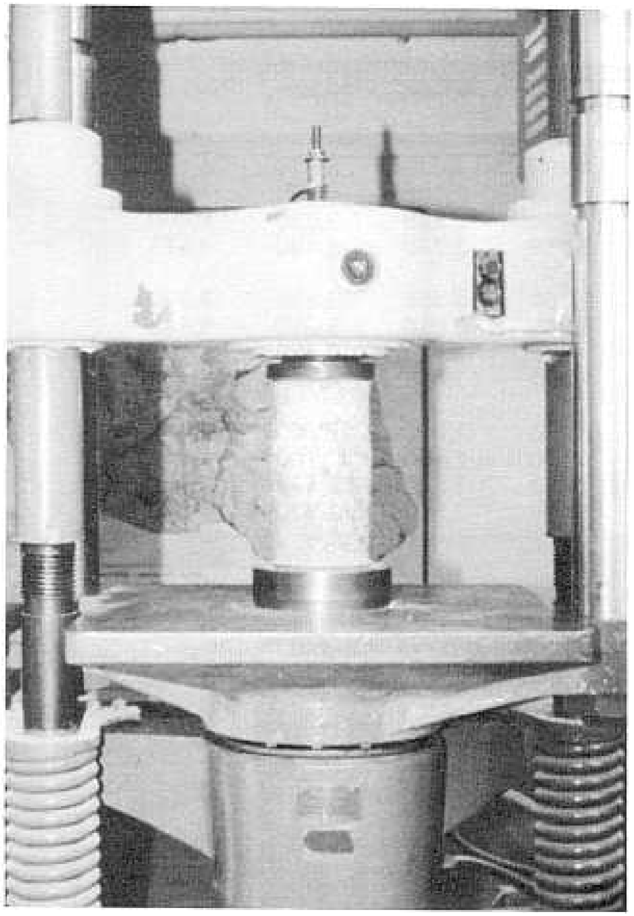

Figure 24.–Roller-compacted concrete specimen during compressive strength test. P-801-D-81411

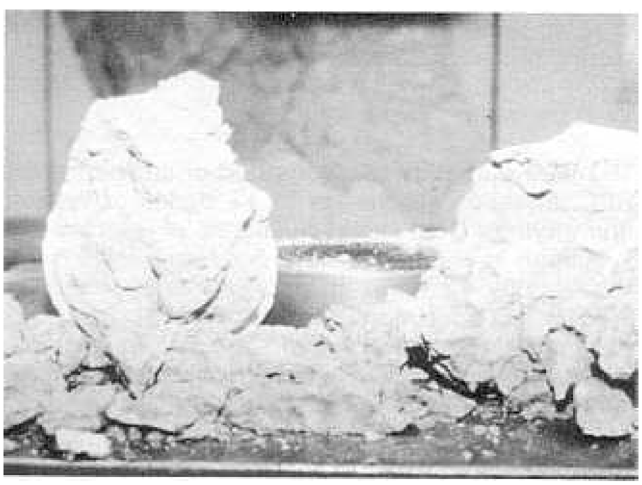

Figure 25.–View of a roller-compacted concrete specimen following compressive strength testing. The test specimen (28-days old) contained 20-percent fines and was compacted with 80 blows per lift. P-801-D-81412

Results of tests performed on the two specimens were averaged to provide an average compressive strength. Average compressive strengths at 7, 28, 90, 180, and 360 days after compaction are summarized in table 6.

- Compressive strength test results are summarized in table D1 and on figures 26 through 39.
- Compressive strength of the RCC generally increased with increased compactive effort, as shown on figures 26 through 28.
- Compressive strength of RCC generally decreased with addition of fines, as shown on figures 29 through 33.
- Figures 34 through 36 show an increase in compressive strength with time for all RCC mixes.
- Figures 37 through 39 are plots showing average compressive strength versus water-cementitious materials ratio for each fines content.

The 90-, 180-, and 360-day compressive strength test results were somewhat erratic. The specimens compacted to the highest unit weights did not consistently have the highest compressive strengths. This may be due to several factors such as aggregate breakdown, variation in water-cementitious materials ratio, and not enough cement paste to fill air voids in the drier mixes (higher compactive efforts).

**Durability Tests**

The purpose of durability testing was to determine if modified soil-cement durability testing procedures could be applied to RCC. Mixes for the durability test RCC specimens were prepared at optimum moisture content determined from the laboratory compaction test.

Six-inch-diameter by 12-inch-high cylindrical RCC specimens were prepared in a similar manner as the compaction and compressive strength test specimens. The specimens were compacted to within ±0.5 percent of maximum dry unit weight, as determined from the laboratory compaction test. Four specimens were prepared at each fines content and compactive effort so that two specimens could be used for W-D durability testing and two specimens for F-T durability testing.

The specimens were cured in a fog room at 100 percent humidity for 7 days. Following the curing period, the specimens were cut 5.77 inches long with a masonry saw (see app. F for calculations).

Figure 40 shows a typical pair of durability test specimens prepared for testing. The test specimens were cut to this length to provide the same relationship of maximum aggregate size to surface

Table 6. - Summary of average compressive strengths — days after compaction.

| Fines content % | Number of blows/lift | Compactive effort ft-lbf/in³ | Average compressive strength—lbf/in² 7-day | 28-day | 90-day | 180-day | 360-day |
|---|---|---|---|---|---|---|---|
| 0 | 27 | 7.2 | 815 | 1,495 | 3,025 | 3,525 | 4,130 |
| | 50 | 13.3 | 1,035 | 1,785 | 2,685 | 4,300 | 4,290 |
| | 80 | 21.2 | 1,400 | 1,980 | 3,245 | 3,830 | 4,600 |
| | 122 | 32.4 | 1,555 | 2,160 | 3,330 | 4,150 | 4,275 |
| 10 | 27 | 7.2 | 690 | 1,165 | 2,555 | 3,110 | 3,270 |
| | 50 | 13.3 | 895 | 1,385 | 3,010 | 3,010 | 3,845 |
| | 80 | 21.2 | 1,070 | 1,605 | 2,925 | 2,850 | 3,680 |
| | 122 | 32.4 | 1,260 | 1,870 | 2,635 | 3,460 | 3,480 |
| 20 | 27 | 7.2 | 470 | 1,015 | 1,890 | 2,300 | 2,690 |
| | 50 | 13.3 | 640 | 1,170 | 1,730 | 2,100 | 2,920 |
| | 80 | 21.2 | 705 | 1,210 | 1,935 | 2,175 | 2,885 |
| | 122 | 32.4 | 985 | 1,475 | 2,305 | 2,520 | 2,990 |

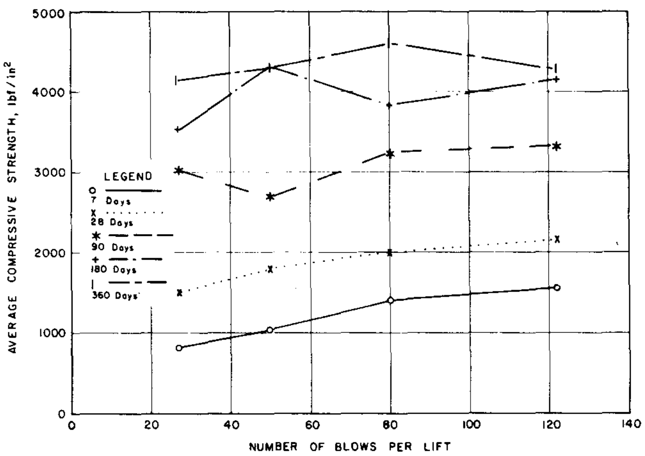


Figure 26.-Roller-compacted concrete — average compressive strength versus number of blows per lift (0% fines).

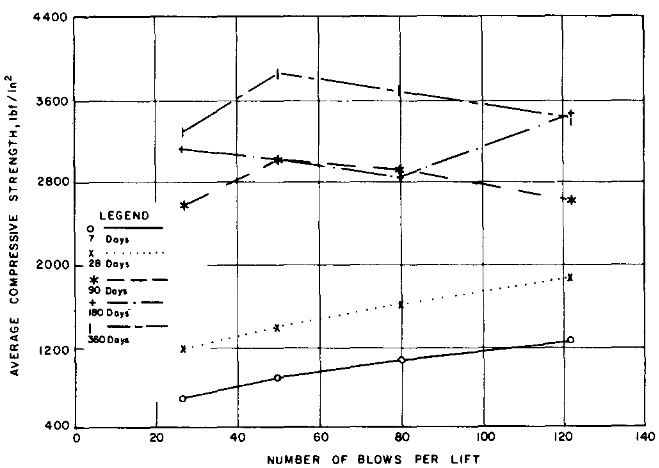


Figure 27.-Roller-compacted concrete — average compressive strength versus number of blows per lift (10% fines).

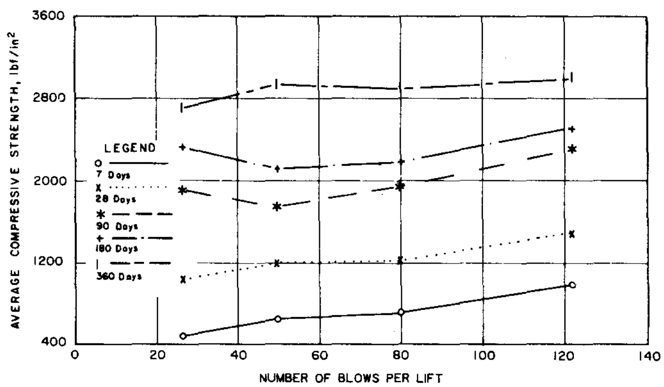


Figure 28.-Roller-compacted concrete — average compressive strength versus number of blows per lift (20% fines).

area as provided by current soil-cement durability testing procedures.

### W-D Durability Tests

The W-D durability test consisted of subjecting the RCC durability specimens to 12 cycles of wetting and drying. One cycle consisted of placing the specimen in water at room temperature for 5 hours followed by 42 hours in a drying oven at 160±5 °F. The test specimens were brushed at the end of each cycle; the total mass of material removed was determined and the percent mass loss was calculated.

### F-T Durability Tests

The F-T durability test consisted of subjecting the RCC durability specimens to 12 cycles of freezing and thawing. One cycle consisted of placing the specimen in a freezing cabinet at -10 °F for 24 hours, followed by 23 hours of thawing in a fog room (100%

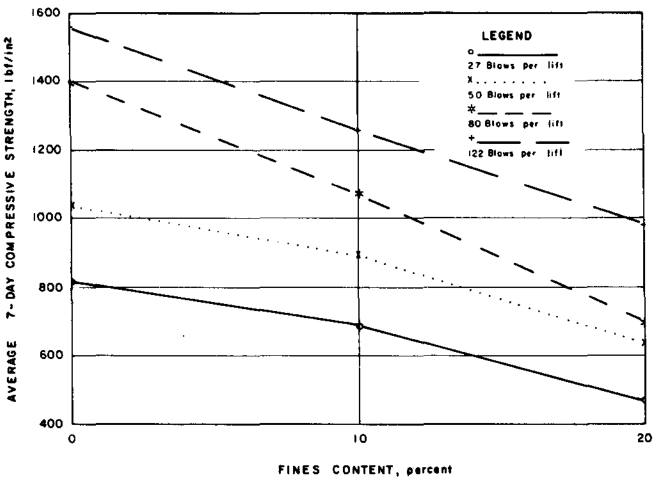


Figure 29.-7-day compressive strength versus fines content.

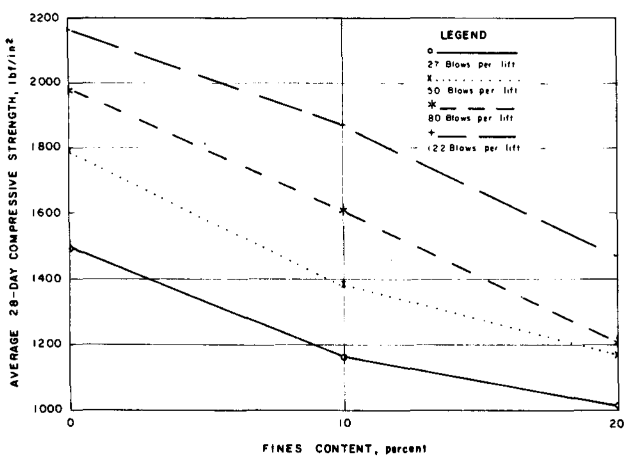


Figure 30.-28-day compressive strength versus fines content.

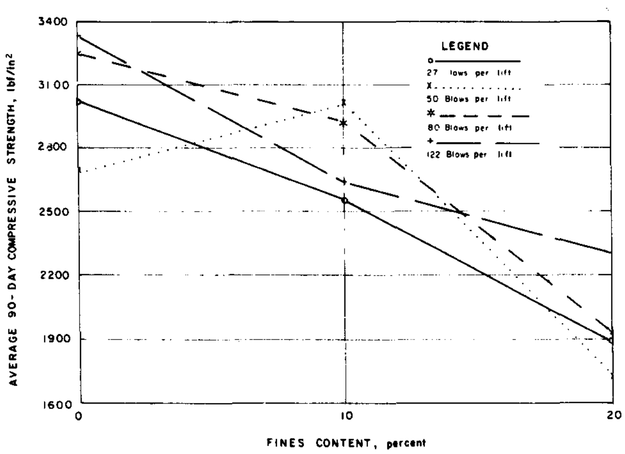


Figure 31.-90-day compressive strength versus fines content.

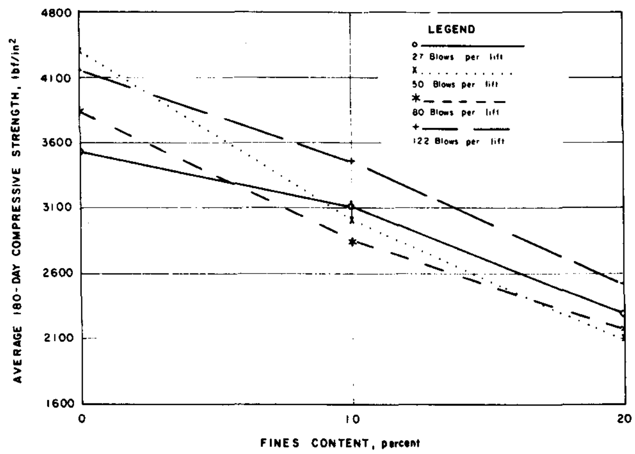


Figure 32.-180-day compressive strength versus fines content.

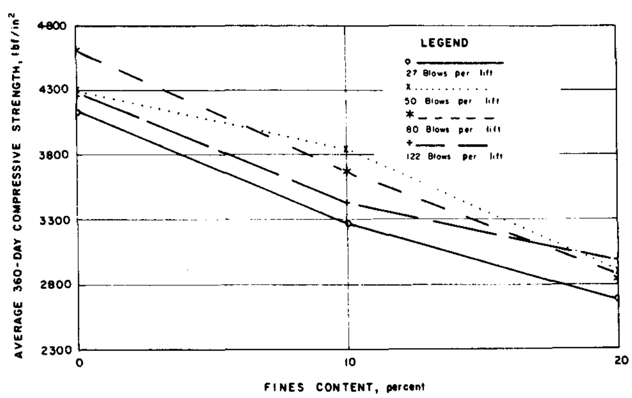


Figure 33.-360-day compressive strength versus fines content.

humidity) at 73.4±3.0 °F. The test specimens were brushed at the end of each cycle; the total mass of material removed was determined and the percent mass loss was calculated.

Figure 41 shows a durability test specimen during brushing.

Appendix E has two detailed descriptions of the RCC W-D and F-T testing procedures.

Results of the tests performed on the two specimens were averaged to provide an average mass loss. Average percent mass losses are summarized in table 7.

The RCC durability test results are summarized in table D1 and on figures 42 and 43.

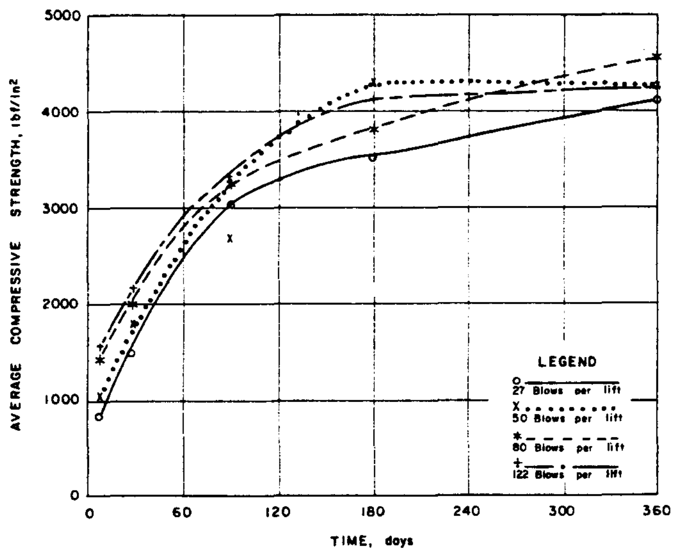


Figure 34.–Roller-compacted concrete — average compressive strength versus time (0% fines).

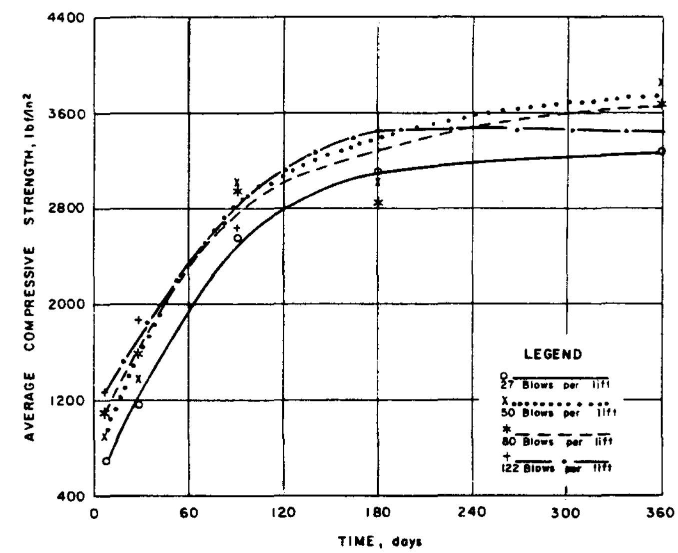


Figure 35.–Roller-compacted concrete — average compressive strength versus time (10% fines).

Figures 42 and 43 are plots showing durability mass loss percentage versus number of blows per lift for each fines content.

As shown, test results were inconclusive indicating that these durability tests may not be the most appropriate for the coarse-grained material. The loss of large pieces of aggregate during durability testing caused inconsistent test results. Small mass losses were recorded for all RCC durability test specimens, including specimens from mixes having low compressive strengths. Normally, soil-cement specimens having low compressive strengths show high durability mass losses; however, RCC durability test

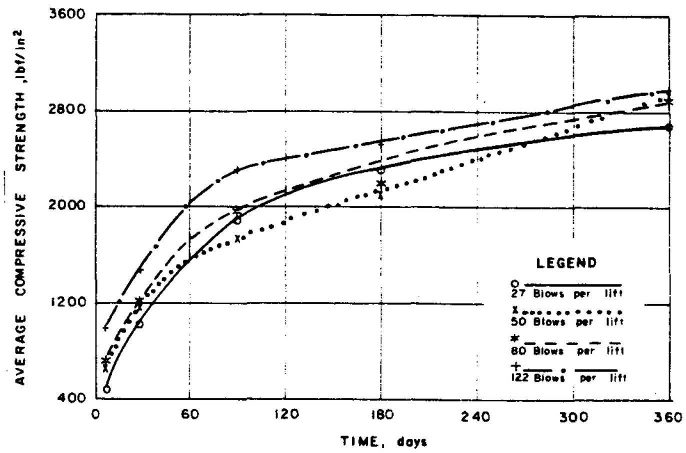


Figure 36.–Roller-compacted concrete — average compressive strength versus time (20% fines).

results did not correlate well with compressive strength test results.

## Gravel Breakdown

Gradation analyses were performed on specimens of RCC compacted at each energy level and fines content to determine the percentage of coarse aggregate breakdown during the compaction process.

Coarse aggregate, for each compacted specimen, was individually prepared and screened over the appropriate sieves for confirmation of the actual gradation prior to mixing and compacting. Specimens were prepared at the optimum moisture contents determined for the compactive effort and fines content and were mixed following the standard mixing procedure.

Batches of 0.20 $ft^3$ RCC were prepared to provide just enough material to completely fill the compaction mold, without excess material, so the entire specimen would be used in the postcompaction gradation test. Specimens were compacted at the selected energy levels using the laboratory impact compaction procedure. After compaction, the specimens were immediately removed from the mold and washed over a Standard No. 4 sieve, as shown on figure 44. Material retained on the No. 4 sieve was ovendried and rescreened over the appropriate sieves. The percentage of coarse aggregate mass loss for each sieve size and total coarse aggregate mass loss were determined based on the initial gradation of the material.

Results of gradation tests to determine percentage of coarse aggregate breakdown caused by compaction are summarized in table 8 and on figures 45 and 46.

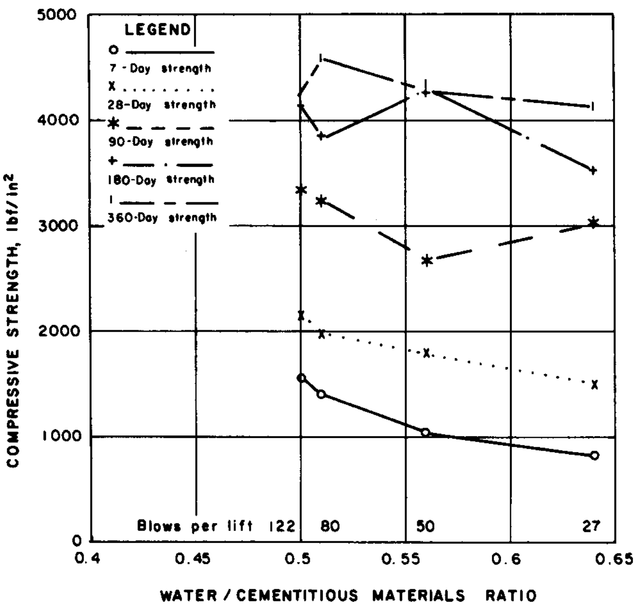


Figure 37.-Roller-compacted concrete — average compressive strength versus water-cementitious materials ratio (0% fines).

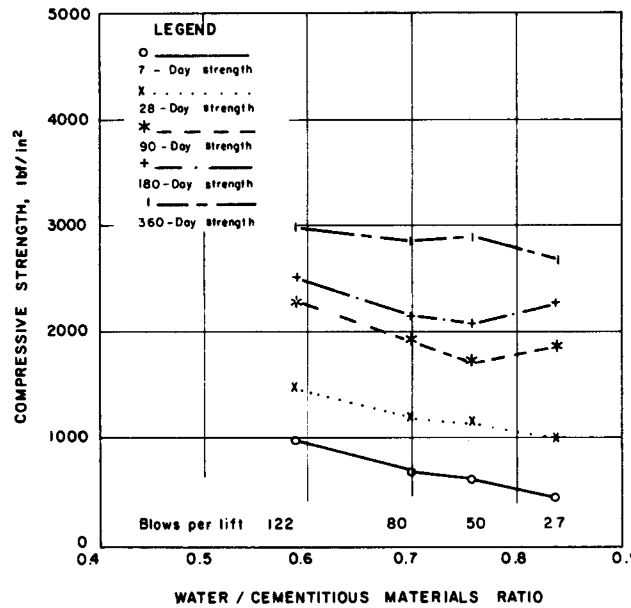


Figure 39.-Roller-compacted concrete — average compressive strength versus water-cementitious materials ratio (20% fines).

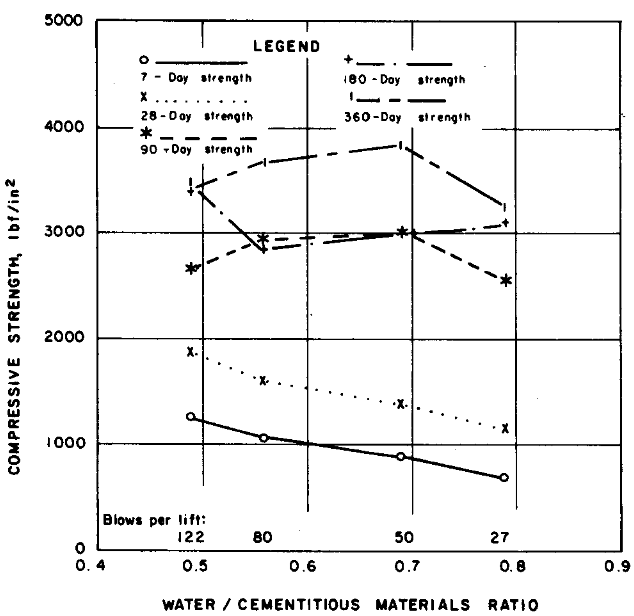


Figure 38.-Roller-compacted concrete — average compressive strength versus water-cementitious materials ratio (10% fines).

Material compacted at all energy levels and fines contents showed some coarse aggregate breakdown. High percentages of coarse aggregate mass loss occurred when 80 and 122 blows per lift were used for compaction. There was minimal increase in coarse aggregate mass loss between compaction at 27 and 50 blows per lift. As expected, the highest percentage of coarse aggregate mass loss occurred in the largest coarse aggregate size (¾ to 1-½ inches), since there could not be breakdown of larger particles to this size. Mass losses in ¾- to 1-½-inch particle size ranged from 4 to 27 percent (fig. 45). Test results indicated that total coarse aggregate mass loss (6 to 17%) increased with compactive effort and decreased with increased fines and moisture content (fig. 46); however, there was significant increase in coarse aggregate mass loss between 50 and 80 blows per lift and minimal increase in coarse aggregate mass loss between 27 and 50 blows per lift.

As aggregate breaks down during compaction, fractured surfaces may not be coated with cement paste and may reflect a decrease in compressive strength and an increase in mass loss in the durability tests. Figure 47 is a view of an RCC compressive strength specimen following testing.

### Index Unit Weight Tests

***Aggregate mix only***.- Minimum and maximum index unit weight tests were performed on the aggregate mixture containing 0-percent fines. Both dry and wet methods were used to obtain maximum index unit weight. Table 9 summarizes the test results.

The tests were performed in accordance with procedures described in the *Earth Manual*, Designation E-12, Relative Density of Cohesionless Soils [8]. Figure 48 shows the vibrating table, mold, and surcharge apparatus used for maximum index unit weight testing.

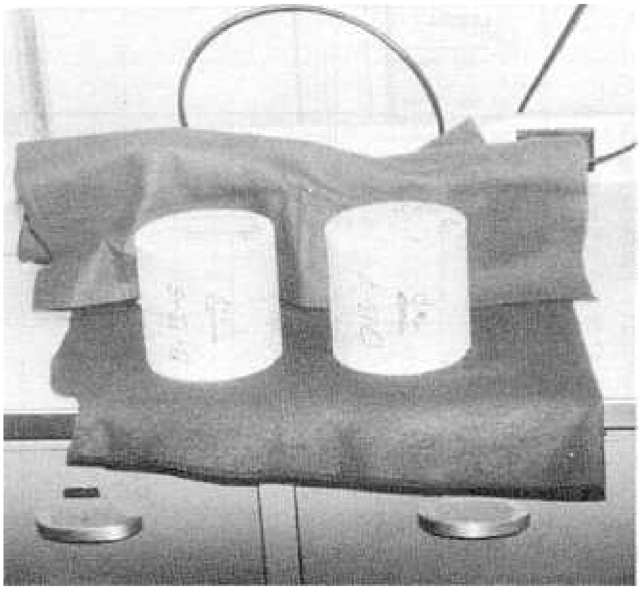

Figure 40.–Typical pair of roller-compacted concrete specimens cut and sized for durability testing. P801-D-81413

Figure 41.–Brushing of roller-compacted concrete durability test specimen. P801-D-81414

Table 7.–Summary of roller-compacted concrete durability tests.

| Fines content, % | Number of blows per lift | Average mass loss % W-D | Average mass loss % F-T |
|---|---|---|---|
| 0 | 27 | 0.4 | 0.6 |
| | 50 | .4 | .4 |
| | 80 | .4 | .2 |
| | 122 | .4 | .3 |
| 10 | 27 | 1.2 | .3 |
| | 50 | 0.6 | .2 |
| | 80 | .6 | .4 |
| | 122 | .6 | .1 |
| 20 | 27 | .5 | .6 |
| | 50 | .4 | 1.0 |
| | 80 | .4 | 1.4 |
| | 122 | .6 | 0.9 |

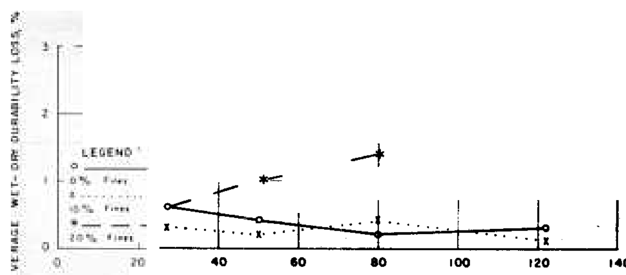


Figure 42.–Roller-compacted concrete — average wet-dry durability test results (12 cycles of testing).

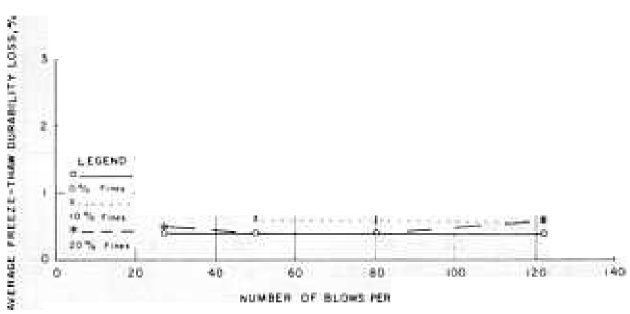


Figure 43.–Roller-compacted concrete — average freeze-thaw durability test results (12 cycles of testing).

***RCC mixes (aggregate, cementitious materials, and fines).***–Minimum and maximum index unit weight tests were performed on dry RCC mixes containing 0, 10, and 20 percent fines. These tests were performed in accordance with procedures described in Designation E-12 of the *Earth Manual* [8]. In addition, wet method maximum index unit weight tests (with modification to the testing procedure) were performed on RCC mixes prepared at the approximate optimum moisture contents determined for each compactive effort and fines content. Because water could not be effectively added to the mixes with cementitious materials during vibration in the mold, the mixes were prepared in advance at optimum moisture content.

Appendix E contains a detailed description of the index unit weight testing procedures used in this study. Table 10 summarizes results of the index unit weight tests. The index unit weight test results are

Figure 44.-Washing and screening roller-compacted concrete over a U.S. Standard No. 4 sieve after compaction for determination of aggregate breakdown. P801-D-81415

summarized in table D2 and on figures 49 through 56.

Plots showing wet and dry unit weights versus calculated optimum moisture contents are shown on figures 49 and 50, respectively.

Summary plots comparing wet and dry unit weights determined from laboratory compaction, maximum index unit weight, and concrete consistency tests are shown on figures 51 through 53 and on figures 54 through 56, respectively.

Test results were erratic indicating that maximum index unit weight tests may not be the most appropriate for the RCC; however, further study should be given to developing a vibratory test for use with RCC, as impact compaction breaks down the coarse aggregate. The index unit weight method of vibration is not adequate for mixes at approximate optimum moisture content that are too dry to flow, and the cementitious materials restrict free movement of added water during vibration. Adding water to improve flow conditions would significantly change the properties of the RCC mixture. The maximum index unit weights determined by the dry method do not provide relevant data when cement and fly ash are present. RCC mixes containing 10 or more percent fines plus cement and fly ash probably contain too high a percentage of fines to provide consistent and accurate data using a current vibratory method.

**Concrete Consistency Tests**

Concrete consistency tests were performed on RCC mixes prepared at the approximate optimum moisture content determined for each compactive effort and fines content.

A model Vebe vibratory table was not available for this testing program, so a mechanically driven vibratory table (with adjustable eccentrics) was adjusted to accommodate the 9-inch-inside-diameter Vebe mold (fig.57). The frequency and amplitude of the vibratory table were calibrated to match that of a concrete Vebe table. A double amplitude of vibration of 0.020 inch at a 60-hertz frequency was used for testing.

The specimen was prepared and placed in a mold, and the mold was secured to the table. A 50-lbm (0.7 $lbm/in^2$) surcharge was placed on top of the specimen. The table was activated and the inside of the mold observed for formation of a "mortar ring." Figure 58 shows the "mortar ring." When the ring formed, vibration was stopped and vibration time recorded. If, following 3 minutes of vibration, a mortar ring had not formed, vibration was stopped, the time recorded, and the wet unit weight determined.

Appendix E has a detailed description of the concrete consistency testing procedure.

Results of concrete consistency tests are summarized in table 11.

Test results demonstrated that "mortar rings" would not form for the drier mixes. With the addition of fines, "mortar rings" would only form at the higher water-cementitious materials ratios. Test results are summarized in table D2.

- Plots showing wet and dry unit weights versus calculated optimum moisture contents are shown on figures 59 and 60, respectively.
- Summary plots comparing wet and dry unit weights determined by laboratory compaction, index unit weight, and concrete consistency tests are shown on figures 51 through 53 and 54 through 56, respectively.

Concrete consistency tests were performed using a mechanically driven vibratory table having adjustable eccentrics, instead of a concrete Vebe vibratory table, thus possibly producing nonstandard concrete consistency test results. The dry mixes (optimum moisture contents obtained from the laboratory compaction test) did not appear to fully "consolidate" and did not form the required "mortar ring." Voids

Table 8.-Summary of gradation test results to determine aggregate breakdown.

| Fines content % | Number of blows/lift | *Percent gravel loss ¾ to 1-½ inches | ⅜ to ¾ inch | ⅜ inch to No. 4 | Total gravel loss |
|---|---|---|---|---|---|
| 0 | 27 | 9 | 6 | 12 | 9 |
| | 50 | 12 | 7 | 6 | 9 |
| | 80 | 22 | 4 | 8 | 12 |
| | 122 | 23 | 17 | 9 | 17 |
| 10 | 27 | 8 | 4 | 14 | 8 |
| | 50 | 10 | 4 | 9 | 8 |
| | 80 | 18 | 10 | 18 | 15 |
| | 122 | 27 | 7 | 4 | 15 |
| 20 | 27 | 4 | 6 | 9 | 6 |
| | 50 | 5 | 11 | 10 | 8 |
| | 80 | 15 | 2 | 4 | 8 |
| | 122 | 17 | 9 | 6 | 11 |

* Percent gravel loss is defined as mass of gravel loss divided by the original mass of gravel.

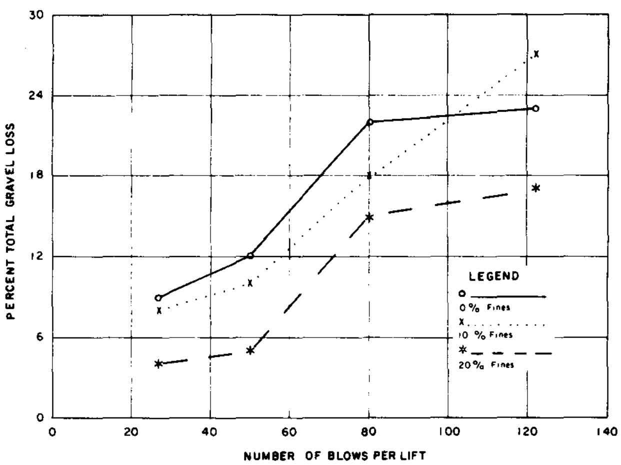


Figure 45.-Roller-compacted concrete ¾ to 1-½ inches gravel loss versus number of blows per lift (0, 10, and 20% fines).

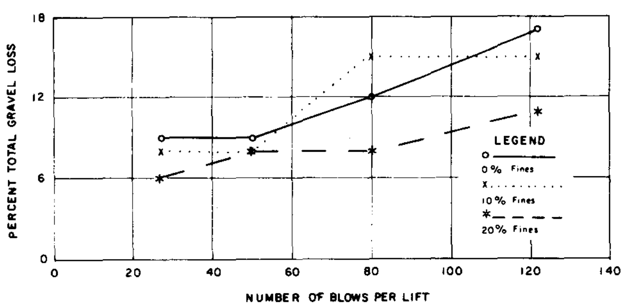


Figure 46.-Roller-compacted concrete — total gravel loss versus number of blows per lift (0, 10, and 20% fines).

were visible in the drier test specimens making volume determination by the water replacement method difficult and possibly inaccurate.

## PERCENT COMPACTION BASED ON THEORETICAL ZERO AIR VOID UNIT WEIGHT

Laboratory test data also were evaluated using traditional concrete theory. The theoretical zero air void unit weight (a wet unit weight) was calculated for each RCC mix design. Sample calculations are shown in appendix F. The wet unit weights at corresponding maximum dry unit weights obtained from the laboratory compaction procedure were divided by the theoretical zero air void unit weight to provide a theoretical percent compaction. In addition, percent compaction data were computed from results of the maximum index unit weight and concrete consistency tests.

The theoretical percent compaction data are summarized in table 12 and on figures 61 through 63. Figures 61 through 63 are plots showing the relationship of wet unit weight at maximum dry unit weight obtained from the laboratory compaction test to the theoretical zero air void unit weight for RCC mixes prepared at each fines content.

Test results show that the highest theoretical percent compaction occurred when 27 and 50 blows per lift were applied to the compaction test specimens. The maximum dry unit weights increased and optimum

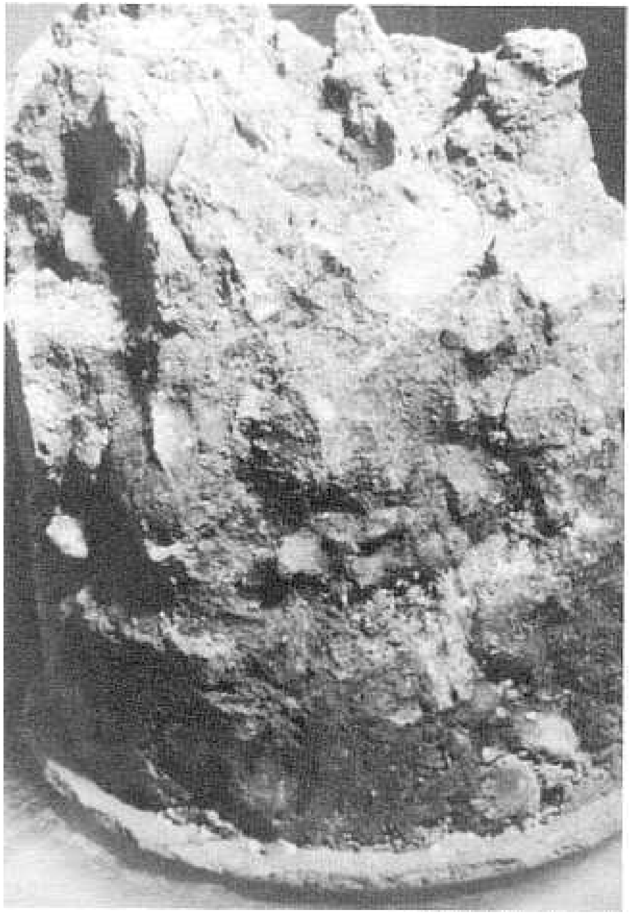

Figure 47.–View of a roller-compacted concrete specimen following compressive strength testing.

Table 9. – Summary of index unit weight tests on aggregate.

| Fines content % | Minimum index unit weight lbf/ft³ | Maximum index unit weight (dry method) lbf/ft³ | Maximum index unit weight (wet method) lbf/ft³ |
|---|---|---|---|
| 0 | 114.4 | 137.0 | 134.8 |

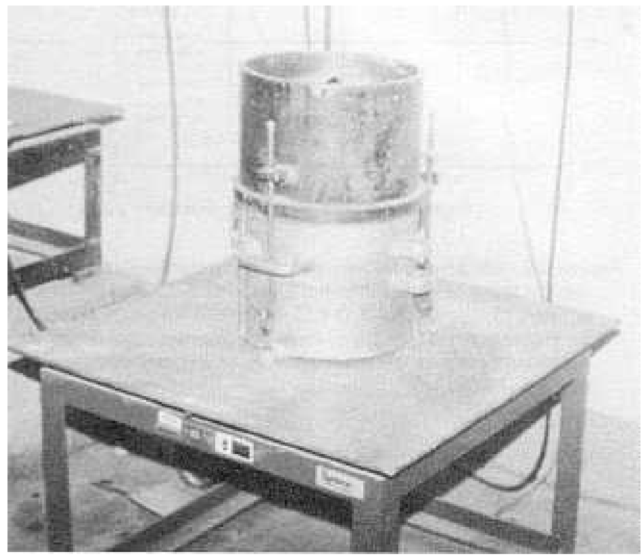

Figure 48.–Vibratory table, mold, and surcharge apparatus used for performing maximum index unit weight tests. P801-D-81417

Table 10. – Summary of index unit weight tests on roller-compacted concrete mixes.

| Fines content % | Number of blows per lift | Calculated optimum moisture content* % | Minimum index unit weight lbf/ft³ | Maximum index unit weight (dry method) lbf/ft³ | Maximum index unit weight (wet method)† lbf/ft³ |
|---|---|---|---|---|---|
| 0 | 27 | 5.8 | 120.8 | 144.2 | 142.3 |
| | 50 | 5.1 | | | 146.7 |
| | 80 | 4.7 | | | 140.3 |
| | 122 | 4.6 | | | 140.5 |
| 10 | 27 | 6.9 | 120.1 | 143.9 | 145.7 |
| | 50 | 6.2 | | | 145.0 |
| | 80 | 5.0 | | | 131.9 |
| | 122 | 4.5 | | | 126.3 |
| 20 | 27 | 7.1 | 117.9 | 141.1 | 136.7 |
| | 50 | 6.4 | | | 128.7 |
| | 80 | 6.0 | | | 128.2 |
| | 122 | 5.2 | | | 115.7 |

* Maximum index unit weight tests performed on RCC mixes prepared at the approximate optimum moisture contents determined from laboratory compaction tests.

† Design optimum moisture content was used to calculate dry unit weight.

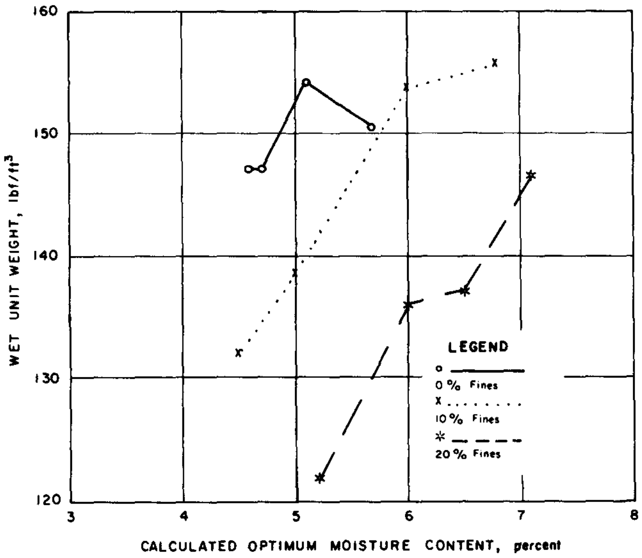


Figure 49.–Roller-compacted concrete maximum index unit weight tests — wet unit weight versus calculated moisture content (0, 10, and 20% fines). Moisture contents selected for relative density testing were the approximate optimum moisture contents determined from laboratory compaction testing of RCC.

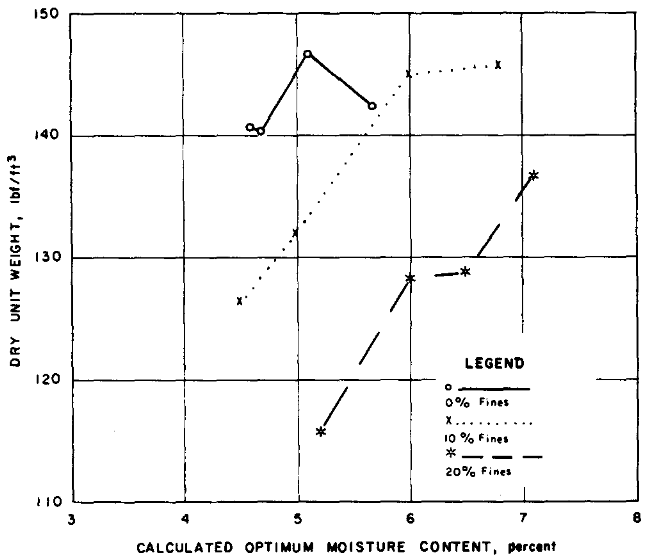


Figure 50.–Roller-compacted concrete maximum index unit weight tests — dry unit weight versus calculated moisture content (0, 10, and 20% fines). Moisture contents selected for relative density testing were the approximate optimum moisture contents determined from laboratory compaction testing of RCC.

moisture contents decreased with increased compactive effort. However, at the higher compactive efforts (80 and 122 blows/lift), the RCC mixes were extremely dry, probably not forming enough cement paste to fill all voids. This indicated that theoretical percent compaction may be lower even with higher unit weight values. At the highest fines content

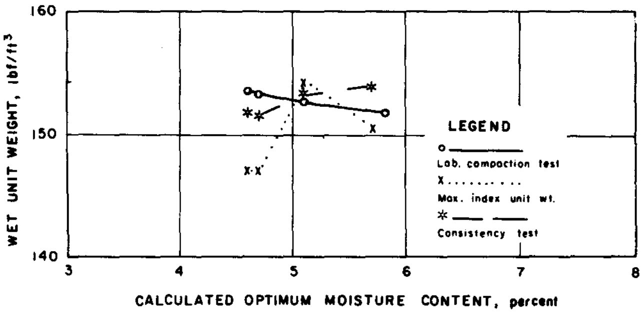


Figure 51.–Roller-compacted concrete laboratory compaction, maximum index unit weight, and concrete consistency tests — wet unit weight versus calculated moisture content (0% fines). Moisture contents selected for testing were the approximate optimum moisture contents determined from laboratory compaction testing of RCC.

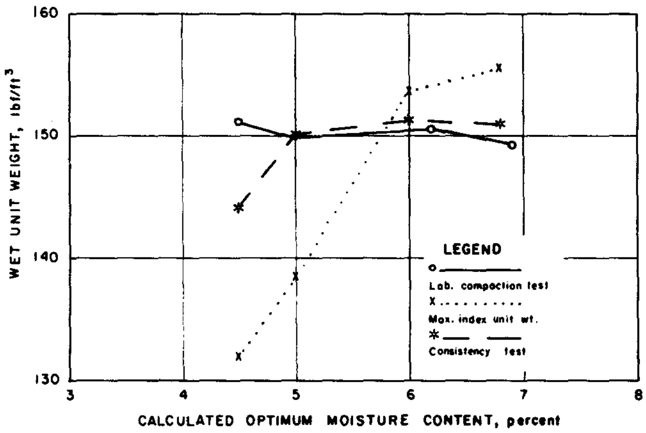


Figure 52.–Roller-compacted concrete laboratory compaction, maximum index unit weight, and concrete consistency tests — wet unit weight versus calculated moisture content (10% fines). Moisture contents selected for testing were the approximate optimum moisture contents determined from laboratory compaction testing of RCC.

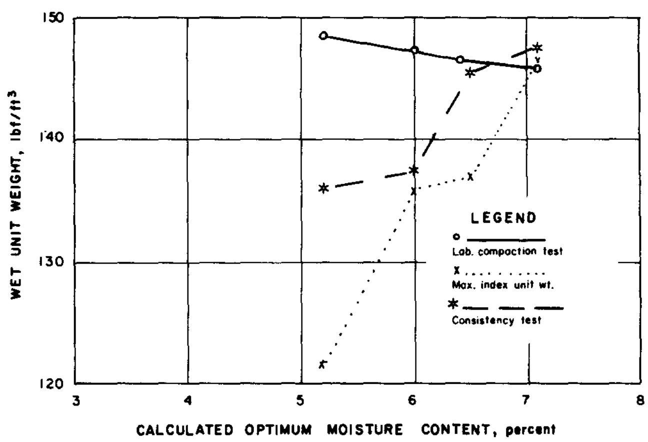


Figure 53.–Roller-compacted concrete laboratory compaction, maximum index unit weight, and concrete consistency tests — wet unit weight versus calculated moisture content (20% fines). Moisture contents selected for testing were the approximate optimum moisture contents determined from laboratory compaction testing of RCC.

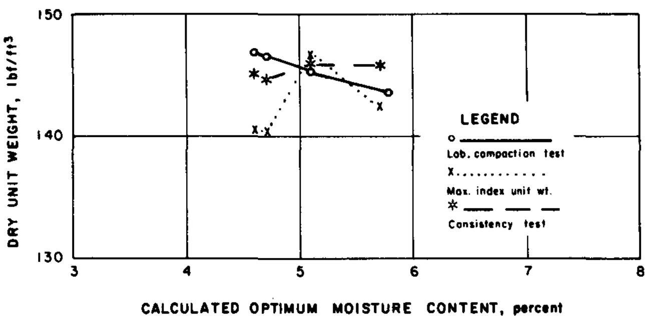


Figure 54.–Roller-compacted concrete laboratory compaction, maximum index unit weight, and concrete consistency tests — dry unit weight versus calculated moisture content (0% fines). Moisture contents selected for testing were the approximate optimum moisture contents determined from laboratory compaction testing of RCC.

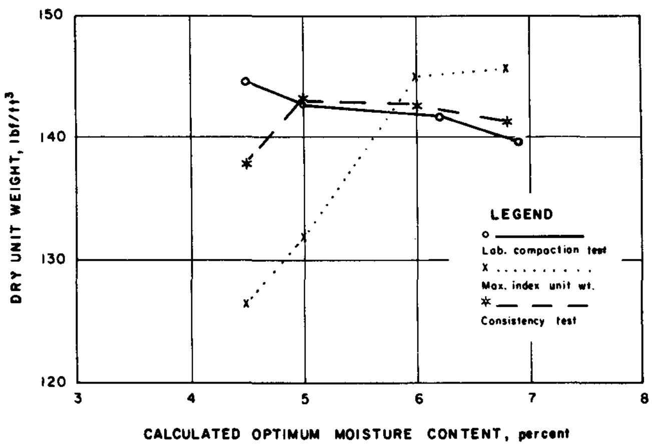


Figure 55.–Roller-compacted concrete laboratory compaction, maximum index unit weight, and concrete consistency tests — dry unit weight versus calculated moisture content (10% fines). Moisture contents selected for testing were the approximate optimum moisture contents determined from laboratory compaction testing of RCC.

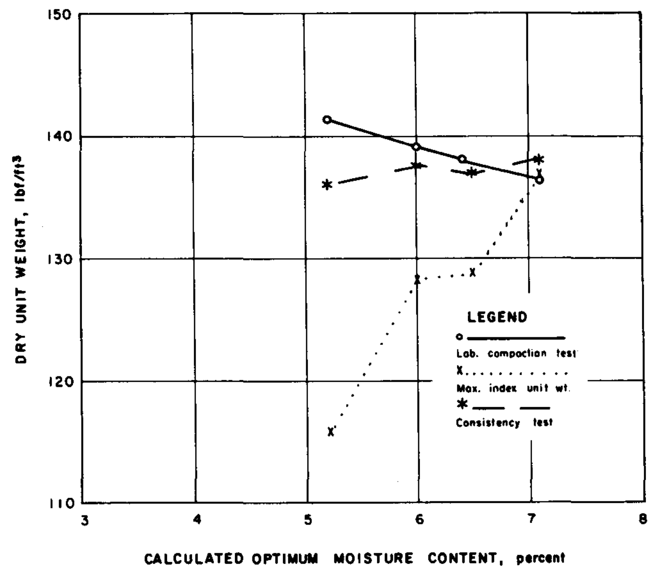


Figure 56.–Roller-compacted concrete laboratory compaction, maximum index unit weight, and concrete consistency tests — dry unit weight versus calculated moisture content (20% fines). Moisture contents selected for testing were the approximate optimum moisture contents determined from laboratory compaction testing of RCC.

(20%), the wet unit weight at the maximum dry unit weight showed a substantially lower theoretical percent compaction for mixes prepared at all moisture contents than those prepared at lower fines contents.

## RECOMMENDATIONS

Further effort should be concentrated on compacting specimens in a standard 6.0-inch-diameter by 4.6-inch-high mold. This mold is currently used in ASTM: D 558, *Standard Test Methods for Moisture-Density Relations of Soil-Cement Mixtures* [6]. The mold was successfully used in an RCC bonding study performed by Tayabji and Okamoto [5].

Additional compressive strength tests should be performed and unit weight comparisons made on sets of specimens compacted at moisture contents slightly wet and dry of optimum moisture content to determine if the laboratory compaction test truly defines the optimum mix design for RCC based on concrete theory.

Standard concrete Vebe (consistency) tests should be performed on RCC mix designs used in this testing program to determine if the mechanically driven vibratory table with adjustable eccentrics provides the same test results as the Vebe vibratory table. A Vebe vibratory table is now available in the Bureau's Concrete and Structural Branch laboratory.

A vibratory (consolidation) test should be developed for mix design and construction control of coarse-grained material as impact compaction breaks down the coarse particles thus changing the properties of the RCC. A vibratory test would better simulate field placement procedures and would not break down the coarse particles. This is extremely important for soil-cement research, as soil-cement with gravel and vibratory compaction are becoming common practice in the Bureau of Reclamation; and currently, standards have not been developed for testing coarse-grained material. The Bureau's Concrete and Structural Branch has developed a laboratory vibratory compaction (consolidation) apparatus; mix designs — used in phase 1 of the multiphase research program — should be used to evaluate the effectiveness of the laboratory vibratory compaction apparatus for both RCC and soil-cement with gravel.

Further comparisons should be made between maximum dry unit weight and theoretical percent compaction of the maximum air-free wet unit weight (at zero air voids), since it is not possible to determine the actual moisture content of the mix.

Figure 57.–Mechanically driven vibratory table having adjustable eccentrics modified to perform concrete consistency tests. P801-D-81418

Figure 58.–"Mortar ring" formed during roller-compacted concrete consistency test. P801-D-81419

Table 11.–Summary of concrete consistency tests.

| Fines content % | Number of blows per lift | Calculated optimum moisture content* % | Water cementitious materials ratio | Wet unit weight lbf/ft³ | Dry unit weight lbf/ft³ | Approximate time of consistency test s |
|---|---|---|---|---|---|---|
| 0 | 27 | 5.8 | 0.64 | 154.0 | 145.7 | 60 |
| | 50 | 5.1 | .56 | 153.2 | 145.8 | 180† |
| | 80 | 4.7 | .51 | 151.5 | 144.7 | 180† |
| | 122 | 4.6 | .50 | 151.7 | 145.0 | 180† |
| 10 | 27 | 6.9 | .79 | 150.9 | 141.3 | 30 |
| | 50 | 6.2 | .69 | 151.3 | 142.7 | 60 |
| | 80 | 5.0 | .56 | 150.1 | 143.0 | 180† |
| | 122 | 4.5 | .49 | 144.1 | 137.9 | 180† |
| 20 | 27 | 7.1 | .84 | 147.7 | 137.9 | 30 |
| | 50 | 6.4 | .76 | 145.7 | 136.8 | 180† |
| | 80 | 6.0 | .70 | 145.7 | 137.5 | 180† |
| | 122 | 5.2 | .59 | 143.1 | 136.0 | 180† |

* Concrete consistency tests performed on RCC mixes prepared at the approximate optimum moisture contents determined from RCC laboratory compaction tests.
† Mortar ring did not form; vibration was stopped and time recorded.

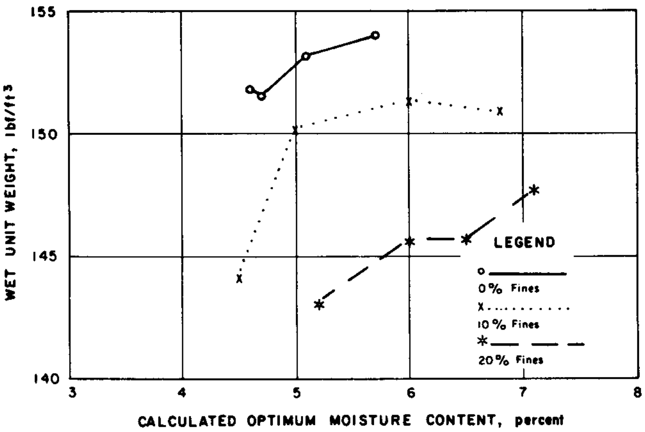


Figure 59.–Roller-compacted concrete consistency tests — wet unit weight versus calculated moisture content (0, 10, and 20% fines). Moisture contents selected for testing were the approximate optimum moisture contents determined from laboratory compaction testing of RCC.

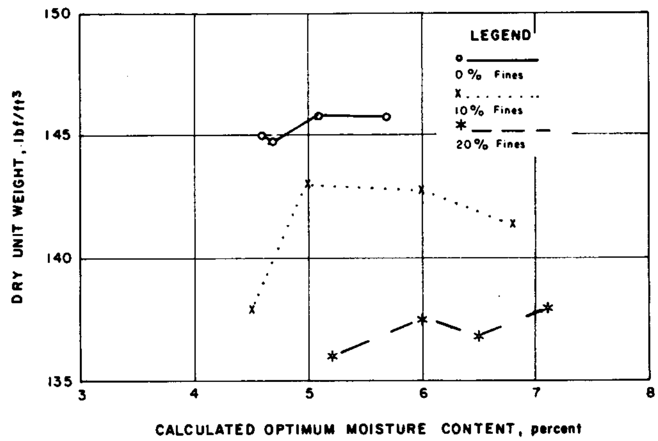


Figure 60.–Roller-compacted concrete consistency test — dry unit weight versus calculated moisture content (0, 10, and 20% fines). Moisture contents selected for testing were the approximate optimum moisture contents determined from laboratory compaction testing of RCC.

Table 12. - Summary of theoretical percent compaction test data.*

| | | | | | Laboratory compaction | | Maximum index unit weight | | Concrete consistency | |
|---|---|---|---|---|---|---|---|---|---|---|
| Fines content % | Number of blows per lift applied by compaction test | Calculated optimum moisture content % | Free moisture lbm/yd³ | Theoretical zero air void wet unit weight lbf/ft³ | Wet unit weight at maximum dry unit weight lbf/ft³ | Theoretical percent compaction % | Wet unit weight from max. index unit weight (wet method) lbf/ft³ | Theoretical percent compaction % | Wet unit weight lbf/ft³ | Theoretical percent compaction % |
| 0 | 27 | 5.8 | 196.1 | 152.3 | 151.7 | 99.6 | 150.4 | 98.8 | 154.0 | 101 |
| | 50 | 5.1 | 168.8 | 153.8 | 152.6 | 99.2 | 154.2 | 100 | 153.2 | 99.6 |
| | 80 | 4.7 | 153.2 | 154.7 | 153.4 | 99.2 | 146.9 | 95.0 | 151.5 | 97.9 |
| | 122 | 4.6 | 149.3 | 154.9 | 153.6 | 99.2 | 147.0 | 94.9 | 151.7 | 97.9 |
| 10 | 27 | 6.9 | 241.8 | 150.0 | 149.4 | 99.6 | 155.6 | 104 | 150.9 | 101 |
| | 50 | 6.2 | 214.5 | 151.3 | 150.6 | 99.5 | 153.7 | 102 | 151.3 | 100 |
| | 80 | 5.0 | 167.6 | 153.8 | 149.8 | 97.4 | 138.5 | 90.0 | 150.1 | 97.6 |
| | 122 | 4.5 | 148.1 | 154.9 | 151.1 | 97.5 | 132.0 | 85.2 | 144.1 | 93.0 |
| 20 | 27 | 7.1 | 252.4 | 149.3 | 146.0 | 97.8 | 146.4 | 98.1 | 147.7 | 98.9 |
| | 50 | 6.4 | 225.0 | 150.7 | 146.7 | 97.3 | 137.1 | 91.0 | 145.7 | 96.7 |
| | 80 | 6.0 | 209.4 | 151.5 | 147.3 | 97.2 | 135.9 | 89.7 | 145.7 | 96.2 |
| | 122 | 5.2 | 178.2 | 153.2 | 148.6 | 97.0 | 121.7 | 79.4 | 143.1 | 93.4 |

* Theoretical percent compaction is defined as the wet unit weight obtained by the laboratory test divided by the theoretical zero air void unit weight.

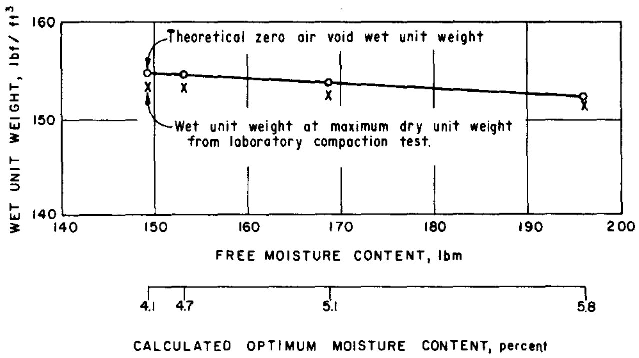


Figure 61.–Wet unit weight versus moisture content (0% fines).

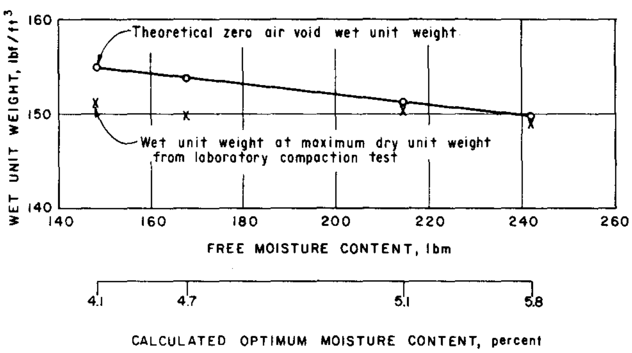


Figure 62.–Wet unit weight versus moisture content (10% fines).

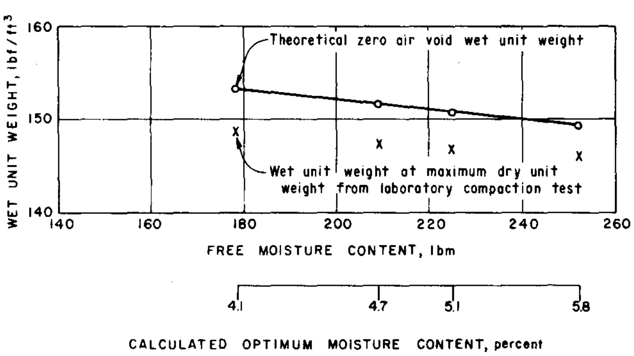


Figure 63.–Wet unit weight versus moisture content (20% fines).

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# APPENDIX A

## Terminology

## TERMINOLOGY

Abbreviations following the definitions are used to refer to the source of the definition:

ASTM - American Society for Testing and Materials
ACI - American Concrete Institute

### Absorbed Moisture

Water held mechanically in a soil or rock mass and having physical properties not substantially different from ordinary water at the same temperature and pressure (ASTM).

### Absorption

The process by which a liquid is drawn into and tends to fill permeable pores in a porous solid body; also the increase in weight [mass] of a porous solid body resulting from the penetration of a liquid into its permeable pores (ACI).

### Aggregate

Granular material, such as sand, gravel, crushed stone, and iron blast-furnace slag, used with a cementing medium to form a hydraulic-cement concrete or mortar (ACI).

### Air Void

A space in cement paste, mortar, or concrete filled with air; an entrapped air void is characteristically 1 mm or more in size and irregular in shape; an entrained air void is typically between 10 and 1,000 µm in diameter and spherical or nearly so (ACI).

### Batching

Weighing [determining the mass] or volumetrically measuring and introducing into the mixer the ingredients for a batch of concrete or mortar (ACI).

### Batch Weights (Mass)

The weights [mass] of the various materials (cement, water, the several sizes of aggregate, and admixtures if used) of which a batch of concrete is composed (ACI).

### Calculated Moisture Content

The moisture content of the RCC (roller-compacted concrete) mix as calculated using batch masses (not an ovendried moisture content).

Cap (Sulfur Cap)

A smooth plane surface of suitable material [sulfur] bonded to the bearing surfaces of test specimens to ensure uniform distribution of load during strength testing (ACI).

Compaction Curve

A curve showing the relationship between dry unit weight and moisture content of RCC for a given compactive effort.

Compaction Test

A laboratory compacting procedure whereby a soil at a known moisture content is placed in a specified manner into a mold of given dimensions, subjected to a compactive effort of controlled magnitude, and the resulting dry unit weight determined. The procedure is repeated for various moisture contents sufficient to establish a relation between moisture content and dry unit weight (similar to ASTM).

Compressive Strength

The load per unit area at which an unconfined cylindrical specimen of soil or rock will fail in a simple compression test. Commonly, the failure load is the maximum that the specimen can withstand in the test (ASTM).

Consistency

The relative mobility or ability of freshly mixed concrete or mortar to flow; the usual measurements are slump for concrete, flow for mortar or grout, and penetration resistance for neat cement paste (ACI).

Fines

Portion of soil finer than a No. 200 (75 μm) U.S. Standard sieve (ASTM).

Fly Ash

The finely divided residue resulting from the combustion of ground or powdered coal and which is transported from the firebox through the boiler by flue gases (ACI).

Free Moisture

Moisture having essentially the properties of pure water in bulk; moisture not absorbed by aggregate (ACI).

Gravel

Particles of rock that will pass a 3-inch (75 mm) U.S. Standard sieve and be retained on a No. 4 (4.75 mm) U.S. Standard sieve.

Grout

A mixture of cementitious material and water, with or without aggregate, proportioned to produce a pourable consistency without segregation of the constituents; also a mixture of other composition but of similar consistency (ACI).

Heat of Hydration

Heat evolved by chemical reactions with water, such as that evolved during the setting and hardening of portland cement. The difference between the heat of solution of dry cement and that of partially hydrated cement (ACI).

Hydration

Formation of a compound by the combining of water with some other substance; in concrete, the chemical reaction between hydraulic cement and water (ACI).

Loess

A uniform aeolian deposit of silty material having an open structure and relatively high cohesion due to cementation of clay or calcareous material at grain contacts (ASTM).

Maximum Unit Weight

The dry unit weight defined by the peak of a compaction curve.

Mortar

A mixture of cement paste and fine aggregate; in fresh concrete, the material occupying the interstices among particles of coarse aggregate; in masonry construction, mortar may contain masonry cement, or may contain hydraulic cement with lime (and possibly other admixtures) to afford greater plasticity and workability than are attainable with standard hydraulic cement mortar (ACI).

Optimum Moisture Content

The moisture content defined by the peak of a compaction curve.

Paste Content

Proportional volume of cement paste in concrete, mortar, or the like, expressed as volume percent of the entire mixture (ACI).

Theoretical Percent Compaction

The wet unit weight obtained from the laboratory test divided by the theoretical zero air void wet unit weight and multiplied by 100 to change to percent.

Portland Cement

A hydraulic cement produced by pulverizing clinker consisting essentially of hydraulic calcium silicates, and usually containing one or more of the forms of calcium sulfate as an interground addition (ACI).

Pozzolan

A siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value, that will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties (ACI).

Relative Density

The ratio of (1) the difference between the void ratio of a cohesionless soil in the loosest state and any given void ratio to (2) the difference between its void ratios in the loosest and in the densest states (ASTM).

RCC (Moisture) Content

Ratio of the mass of water to the total dry mass of a roller-compacted concrete mixture, expressed as a percentage.

RCC (Roller-Compacted Concrete)

A mixture of portland cement (including fly ash), 3/4-inch or larger aggregate, and water; compacted by rolling. The aggregate used is generally of controlled grading to produce more uniform concrete properties.

Sand

Particles of rock that will pass the No. 4 (4.75 mm) U.S. Standard sieve and be retained on the No. 200 (75 µm) U.S. Standard sieve (similar to ASTM).

SSD (Saturated Surface Dry)

Condition of an aggregate particle when the permeable voids are filled with water and no water is on the exposed surfaces.

Slump

A measure of consistency of freshly mixed concrete, mortar, or stucco equal to the subsidence measured to the nearest 1/4 inch (6 mm) of the molded specimen immediately after removal of the slump cone (ACI).

Soil-Cement

A mixture of soil, portland cement, and water that (as the cement hydrates) forms a material with higher strength than the untreated soil. Depending on the amount of water used, it can be placed as a compacted material, as a mortar, or as a slurry.

Temperature Rise

The increase of temperature caused by absorption of heat or internal generation of heat, as by hydration of cement in concrete (ACI).

Theoretical Zero Air Void Unit Weight

Maximum wet unit weight that can be obtained for an RCC mix design, assuming all voids are filled with cement paste.

Vibration

Energetic agitation of freshly mixed concrete during placement by mechanical devices either pneumatic or electric, that create vibratory impulses of moderately high frequency that assist in consolidating the concrete in the form or mold (ACI).

Water-Cement [Cementitious Materials] Ratio

The ratio of the amount of water, exclusive only of that absorbed by the aggregates, to the amount of cement [cementitious materials] in a concrete or mortar mixture; preferably stated as a decimal by weight [mass] (ACI).

WRA (Water Reducing Agent)

A material which either increases slump of freshly mixed mortar or concrete without increasing water [moisture] content or maintains workability with a reduced amount of water [moisture], the effect being due to factors other than air entrainment (ACI).

# APPENDIX B

## Roller-Compacted Concrete Materials and Test Data

7-1734 (8-71)
Bureau of Reclamation

PROJECT Roller-Compacted Concrete Research Material Bonny Loess

| IDENTIFICATION | | | | PARTICLE-SIZE FRACTIONS IN PERCENT | | | | | | CONSISTENCY LIMITS | | | SPECIFIC GRAVITY | | | | COMPACTION TEST | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | FINES | | | | | | | | | | PLUS NO. 4 | | | | | | |
| SAMPLE NUMBER 23J-4 | SPECIMEN NUMBER | DEPTH - feet (m) | CLASSIFICATION SYMBOL | SMALLER THAN 0.005 mm | 0.005 TO 0.074 mm | SAND NO. 200 (0.074 mm) TO NO. 4 (4.76 mm) | GRAVEL NO. 4 (4.76 mm) TO 3 IN. (76.2 mm) | COBBLES 3 IN. (76.2 mm) TO 5 IN. (127 mm) | OVERSIZE LARGER THAN 5 IN. (127 mm) | LIQUID LIMIT - % | PLASTICITY INDEX - % | SHRINKAGE LIMIT - % | MINUS NO. 4 | BULK | APPARENT | ABSORPTION - % | Maximum DRY UNIT WEIGHT-lbf/ft$^3$ (gm/cm$^3$) | OPTIMUM MOISTURE CONTENT - % | PENETRATION RESISTANCE - lbf/in$^2$ (kg/cm$^2$) | |
| | A | | ML | 15 | 66 | 19 | | | | 22 | 2 | | 2.65 | | | | | | | |
| | B | | CL-ML | 10 | 73 | 17 | | | | 25 | 4 | | 2.60 | | | | | | | |
| | C | | CL-ML | 10 | 74 | 16 | | | | 24 | 4 | | 2.63 | | | | | | | |
| | D | | CL-ML | 10 | 74 | 16 | | | | 27 | 7 | | 2.63 | | | | | | | |
| | E | | CL-ML | 11 | 74 | 15 | | | | 26 | 5 | | 2.64 | | | | | | | |
| | F | | ML | 10 | 74 | 16 | | | | 24 | 3 | | 2.63 | | | | | | | |
| | G | | CL-ML | 18 | 58 | 24 | | | | 24 | 4 | | 2.64 | | | | | | | |
| | H | | CL-ML | 11 | 70 | 19 | | | | 25 | 5 | | 2.63 | | | | | | | |
| | | AVERAGE | CL-ML | 12 | 70 | 18 | | | | 25 | 4 | | 2.63 | | | | | | | |
| | I | | | | | | | | | | | | | | | | 108 | 14.8 | 2200 | |

*NOTE: Numbers in parentheses are metric equivalents of numbers directly above.*

GPO 835-198

Table B1.–Summary of physical properties test results — laboratory compaction.

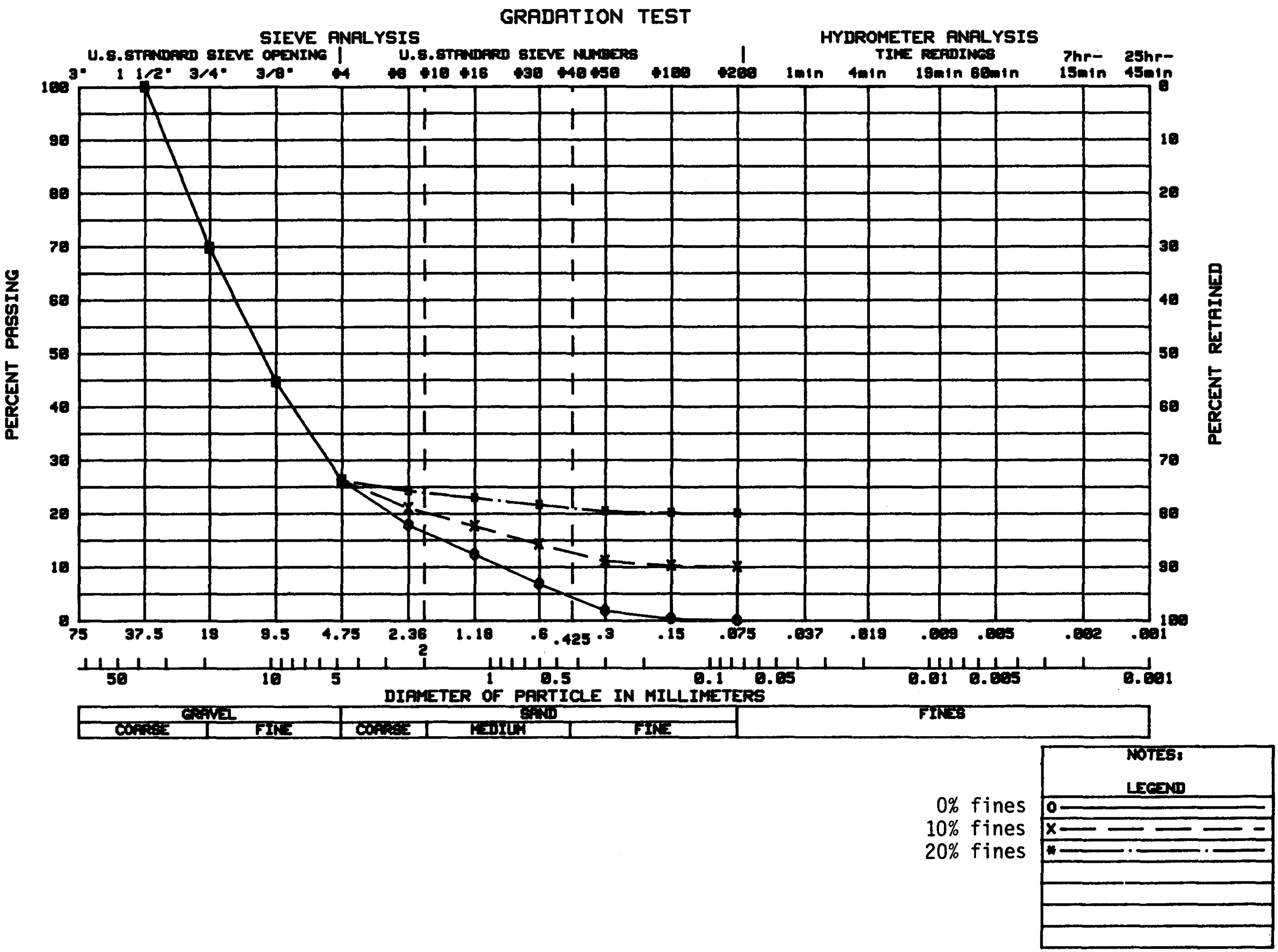
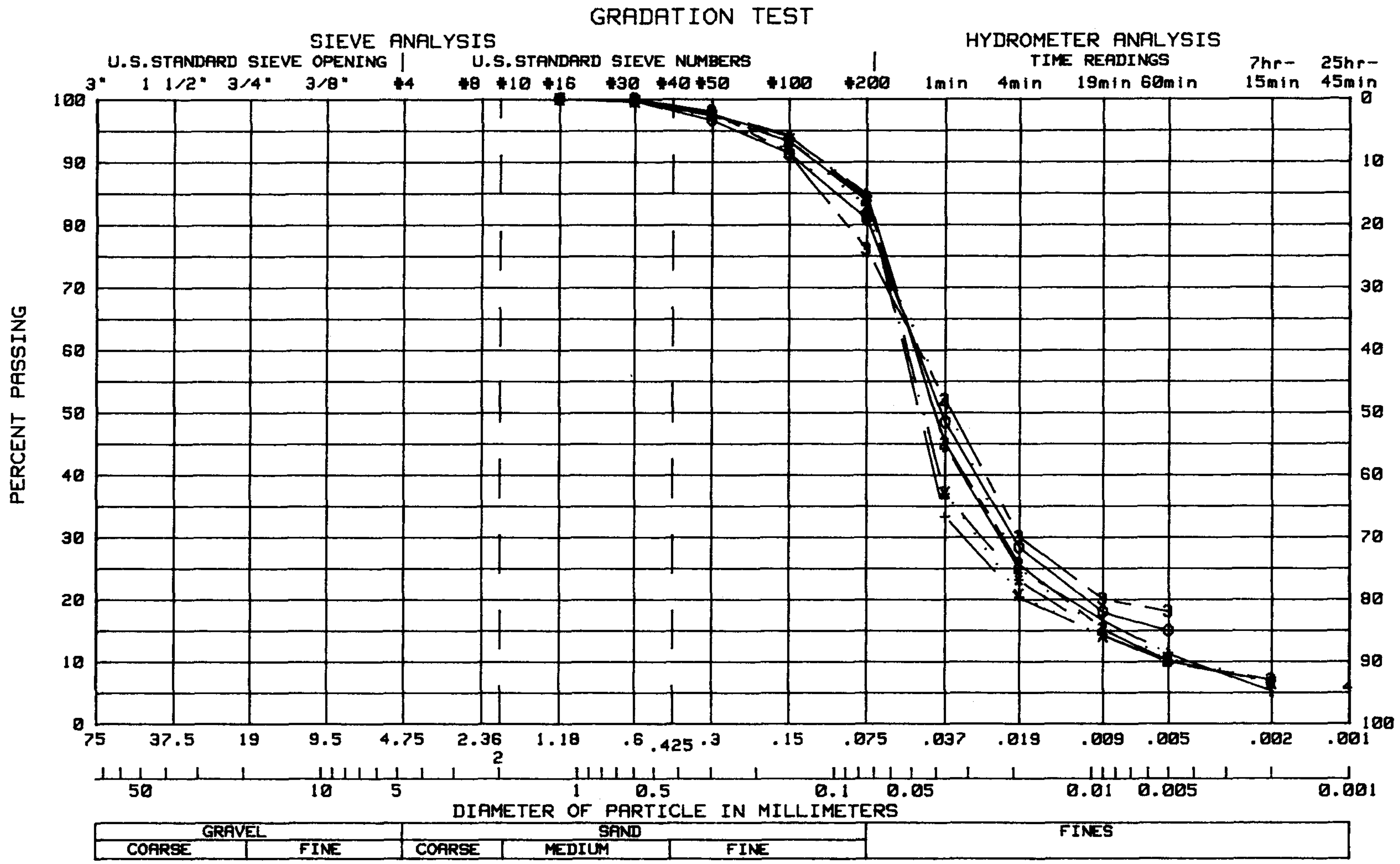



Figure B1.-Gradation test of aggregate for soil-cement research with 0, 10, and 20 percent fines.




PREPARED BY jjc

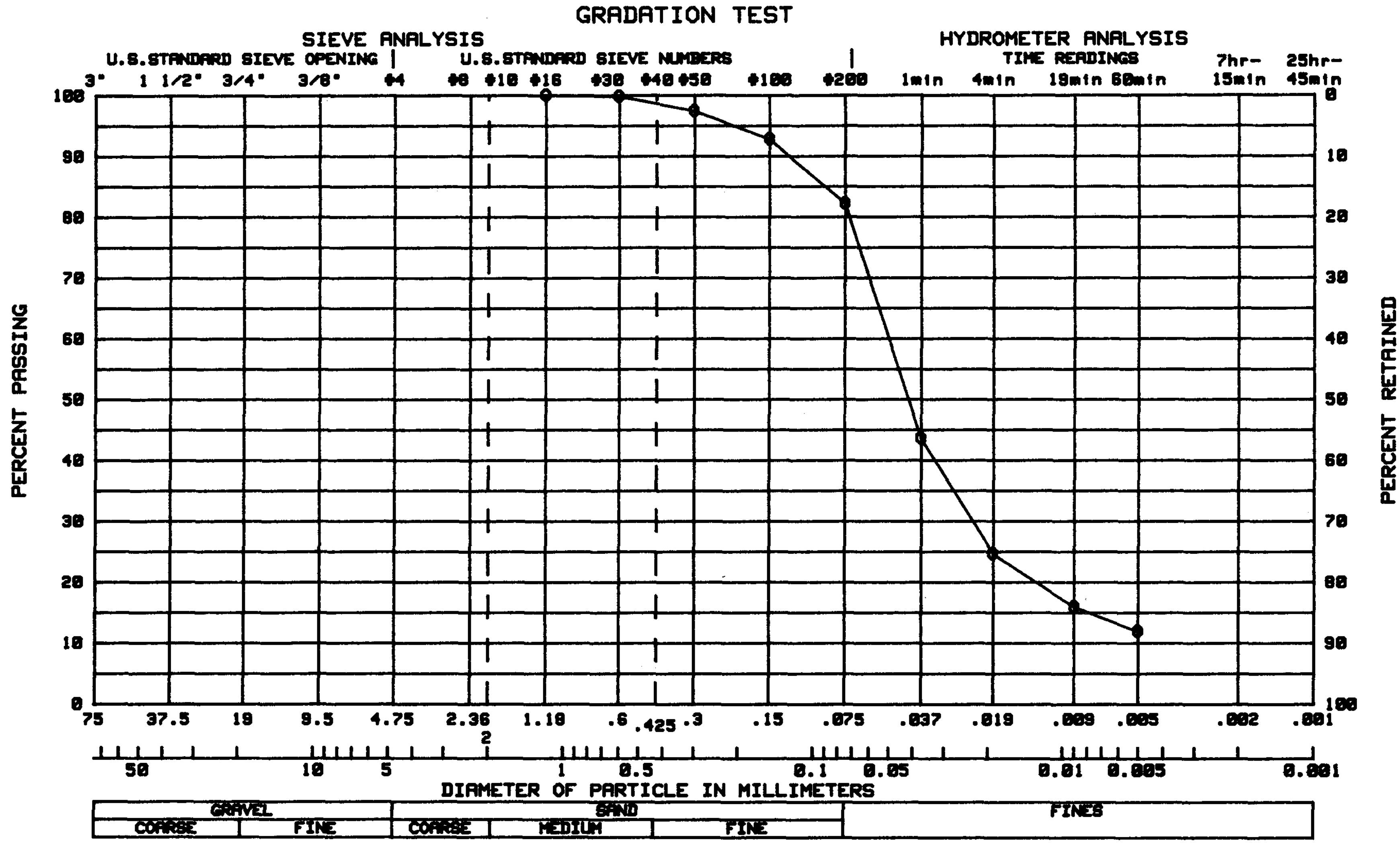
CHECKED BY JJC

| SAMPLE NO. | HOLE NO. | ELEV. OR DEPTH | UNIFIED SOIL CLASSIFICATION | | | | ATTERBERG LIMITS | | | SPECIFIC GRAVITY | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | GROUP SYMBOL | % GRAVEL | % SAND | % FINES | LIQUID LIMIT (%) | PLASTICITY INDEX (%) | SHRINKAGE LIMIT (%) | MINUS NO. 4 | OTHER |
| 23J-4A | | | ML | | 19 | 81 | 22 | 2 | | 2.65 | |
| 23J-4B | | | CL-ML | | 17 | 83 | 25 | 4 | | 2.60 | |
| 23J-4C | | | CL-ML | | 16 | 84 | 24 | 4 | | 2.63 | |
| 23J-4D | | | CL-ML | | 16 | 84 | 27 | 7 | | 2.63 | |
| 23J-4E | | | CL-ML | | 15 | 85 | 26 | 5 | | 2.64 | |
| 23J-4F | | | ML | | 16 | 84 | 24 | 3 | | 2.63 | |
| 23J-4G | | | CL-ML | | 24 | 76 | 24 | 4 | | 2.64 | |
| 23J-4H | | | CL-ML | | 19 | 81 | 25 | 5 | | 2.63 | |

NOTES:

LEGEND
0
X
*
+
1
2
3
4

Figure B2.–Gradation test.




| SAMPLE NO. | HOLE NO. | ELEV. OR DEPTH | UNIFIED SOIL CLASSIFICATION GROUP SYMBOL | % GRAVEL | % SAND | % FINES | ATTERBERG LIMITS LIQUID LIMIT(%) | PLASTICITY INDEX(%) | SHRINKAGE LIMIT(%) | SPECIFIC GRAVITY MINUS NO. 4 | OTHER | NOTES: LEGEND |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 23J-4 | | | CL-ML | | 18 | 82 | 25 | 4 | | 2.63 | | O ———— |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |

Figure B3.–Gradation of Bonny loess for soil-cement research — average of eight tests.

7-1461
(2-58)
BUREAU OF RECLAMATION

BONNY LOESS (Sample No. 23J-4)

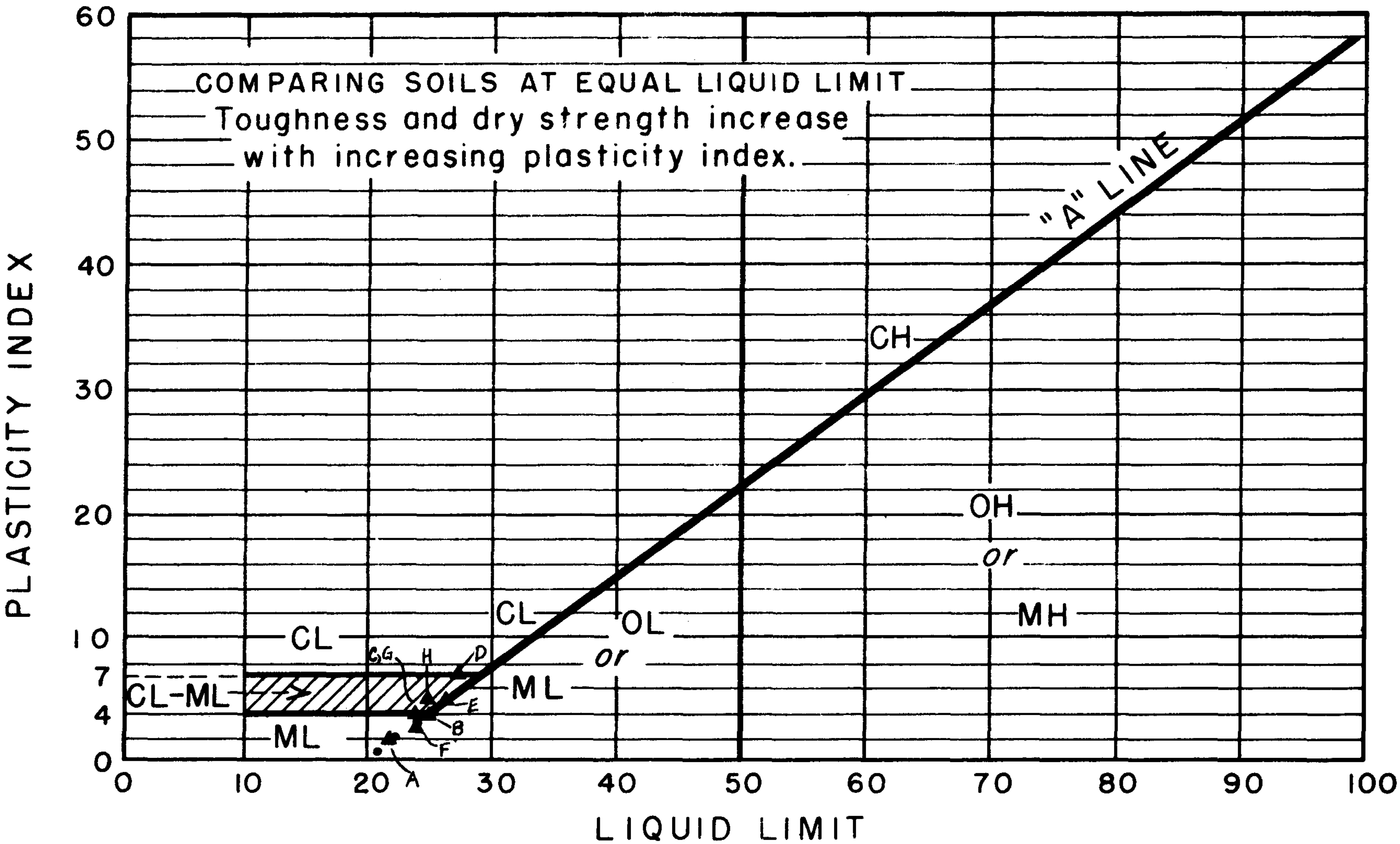



Figure B4.–Plasticity chart for laboratory classification of fine-grained soils.

7-1414 (8-70)
Bureau of
Reclamation

## COMPACTION - PENETRATION RESISTANCE CURVES

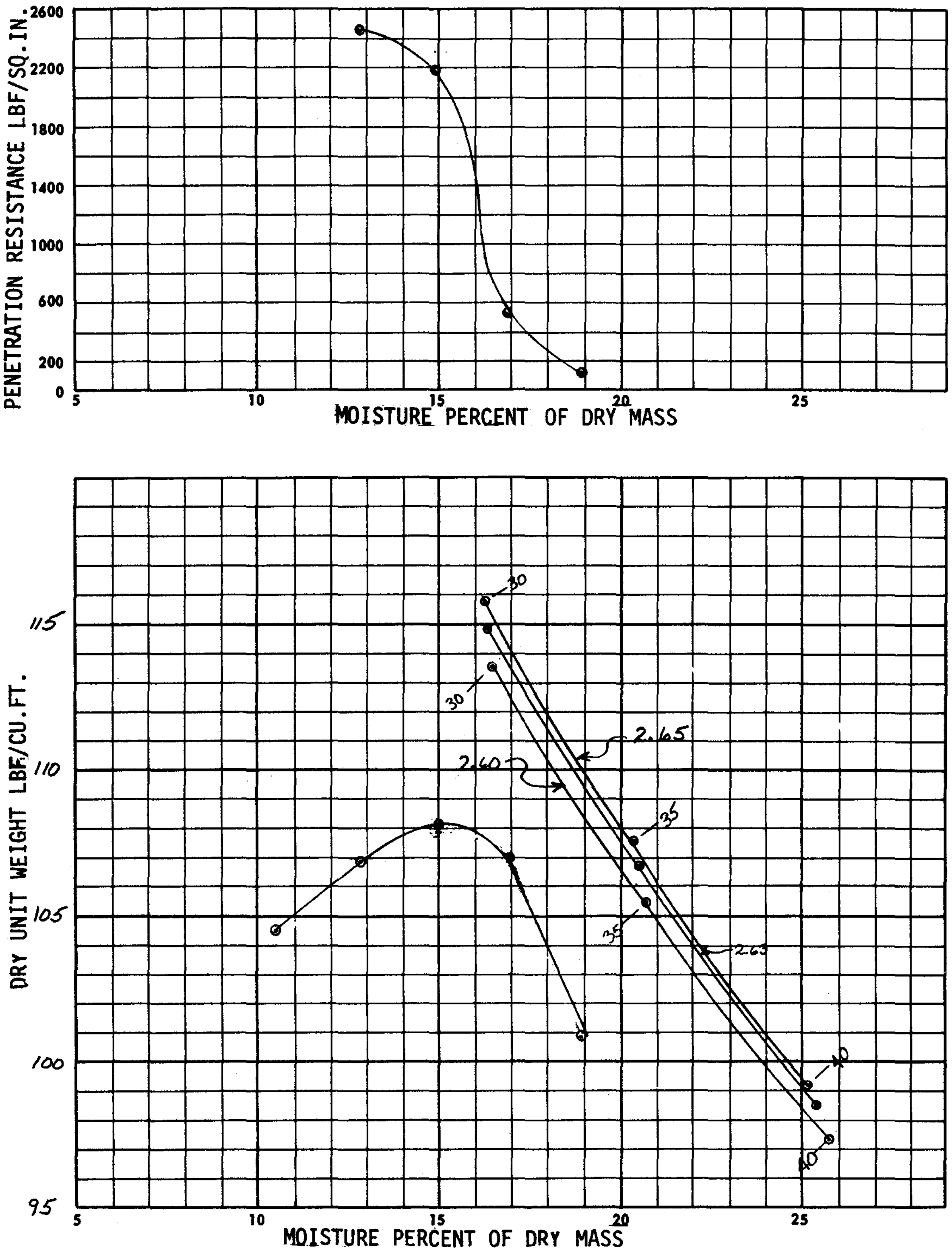



Figure B5.–Compaction – penetration resistance curves.

INFORMATIONAL ROUTING

Memorandum
Chief, Concrete and Structural Branch

Denver, Colorado
June 17, 1975

ACTING Chief, Applied Sciences Branch

Petrographic Examination of Clear Creek Aggregate - Denver Office - U.S. Bureau of Reclamation

Petrographic examination by: E. F. Monk

Petrographic referral code: 75-27

Sample No. M-3864

Material: Plant processed sand and gravel

Source: Plant processed sand and coarse aggregate from Brannan Sand and Gravel Company, Clear Creek, pit No. 10, located at 63rd and Bryant Street, Denver, Colorado.

## Conclusions

Gravel and sand comparable to laboratory sample No. M-3864 are petrographically of satisfactory physical and chemical quality if used as an aggregate in concrete.

Trace amounts of potentially alkali reactive chert and cryptocrystalline quartz particles were observed in the No. 4, No. 30, and in the fine sand (minus No. 30) sieve sizes.

## Summary

The gravel, rounded to angular in shape with about 5.6 percent flattened and elongated particles, is composed mainly of granitics with lesser amounts of metamorphics and minor amounts of pegmatite, schists, sandstone, altered volcanics, quartz and feldspar. The material is physically sound and contains only trace amounts of potentially reactive chert particles in the No. 4 sieve size.

The sand, angular to subangular in shape, is composed of the same rock types found in the gravel plus increasing amounts of monomineralic grains

of quartz, feldspar, micas, amphiboles, epidote, magnetite, garnet, trace amount of chert, and a few miscellaneous detrital minerals in the finer sizes. The sand is physically sound and contains only trace amounts of potentially alkali-reactive chert.

P. H. Lewis

Enclosures

Copy to: 1511 (H. E. Dickey) 2
1511 (O. R. Werner)
230
1520
✓1523

## Table 1

### PETROGRAPHIC EXAMINATION OF COARSE AGGREGATE
Sample No. M-3864

| Rock types | Description of rock types | Physical quality | Percentage by particle count | |
|---|---|---|---|---|
| | | | 3/4 inch | 3/8 inch |
| Granites, includes a few quartz monzonites | Hard, compact, dense, fine to medium grained, pink to gray colored | Satisfactory | 53.7 | 75.0 |
| | Somewhat softened, fractured, slightly weathered | Fair | 13.0 | 2.4 |
| | Deeply weathered, crumbly, highly absorptive | Poor | 1.7 | 0.2 |
| Gneisses, includes a few gneissic granites | Hard, compact, dense, fine to medium grained, to dark gray, streaked | Satisfactory | 12.1 | 10.8 |
| | Somewhat softened, slightly weathered | Fair | 1.7 | 1.2 |
| | Deeply weathered, crumbly, highly absorptive | Poor | -- | 0.5 |
| Pegmatite | Hard, compact, dense, very coarse grained | Satisfactory | 6.5 | -- |
| Schists | Hard, compact, dense, fine grained, micaceous, amphibolitic, sillimanitic, dark gray to black | Satisfactory | 1.3 | -- |
| | Somewhat softened, slightly weathered | Fair | 0.9 | -- |
| Sandstone | Hard, compact, dense, angular to subrounded fine to medium quartz grains, white colored | Satisfactory | 1.3 | -- |
| Altered volcanics; includes rhyolites andesites, andesitic basalts and basalts | Hard, compact, dense, slightly altered, porphyritic to massive, white to light gray to black | Satisfactory | 3.5 | 4.5 |
| | Somewhat softened, moderately weathered | Fair | 1.3 | 0.5 |
| Quartz | Hard, dense, compact, crystalline, clear to translucent, rounded to angular | Satisfactory | 3.0 | 4.4 |
| Feldspar | Hard, dense, compact, dense, crystalline, angular to subrounded, white to pink colored | Satisfactory | -- | 0.5 |

*Alkali reactive rock types.

## Table 2

SUMMARY OF QUALITY OF COARSE AGGREGATE
Sample No. M-3864

| | | Percentage by particle count 3/4 inch | Percentage by particle count 3/8 inch |
|---|---|---|---|
| | Satisfactory | 81.4 | 95.2 |
| Physical | | 16.9 | 4.1 |
| quality | Fair | 1.7 | 0.7 |
| | Poor | | |
| Chemical quality | Alkali-reactive | 0.0 | 0.0 |

(See No. 4 size particles under remarks)

Remarks:

Particle shape: - The gravel particles vary from rounded to angular in shape. About 50 percent of the particles are stream worn and rounded to subrounded in shape. The remainder of the particles shows signs of being crushed and exhibit both rounded stream worn surfaces and broken angular surfaces or having all angular surfaces. Flattened and elongated particles in the coarse aggregate vary from 5.2 percent in the 3/4-inch size to 6.0 percent in the 3/8-inch size.

Coatings and/or encrustations: None observed

No. 4 size: - Essentially same rock and mineral types as found in the 3/4- and 3/8-inch sizes, but becoming more monomineralic. The particle shape is chiefly angular to subangular with about 10 percent rounded to subrounded particles. The physical quality is good. A few particles of black, grays, and brown chert were observed (less than 1 percent).

## Table 3

PETROGRAPHIC EXAMINATION OF COARSE SAND
Sample No.M-3864

| Rock and mineral types | Percentage by particle count | | |
| --- | --- | --- | --- |
| | No. 8 | No. 16 | No. 30 |
| Granites, includes some quartz monzonites | 67.4 | 66.4 | 33.2 |
| Metamorphics; includes schists and gneisses | 7.2 | 3.7 | 1.5 |
| Altered volcanics; includes rhyolites, andesites, andesitic basalts and basalts | 6.8 | 2.7 | 1.8 |
| Quartz (pebbles and vein quartz) | 12.4 | 17.2 | 44.9 |
| Feldspar (clear, white, and pink) | 5.7 | 7.2 | 15.9 |
| Micas (muscovite and biotite) | -- | 0.7 | 0.8 |
| Sillimanite | 0.3 | 1.7 | 1.5 |
| Epidote | 0.2 | 0.2 | -- |
| Magnetite | -- | 0.2 | 0.1 |
| Garnet | -- | -- | 0.1 |
| Chert (includes some cryptocrystalline quartz) | -- | -- | 0.2 |
| Percent unsound | -- | 0.7 | 0.8 |
| Percent alkali reactive | -- | -- | 0.2 |

Remarks: The coarse sand (+ No. 30 sieve size) is angular to subangular in shape and contains about 5.4 percent elongated and flattened particles. The fine sand (-No. 30 sieve size) is angular in shape, contains about 3 percent flattened and elongated particles, and contains decreasing amounts of the fine grained rock types found in the coarse sand with increasing amounts of monomineralic grains of quartz, feldspar, micas, amphiboles, epidote, magnetite, garnet, sillimanite, and a few miscellaneous detrital minerals. The pan size (less than No. 100 sieve size) contained trace amounts of gold.

The fine sand contains about 2-3% physically unsound particles and only trace amounts of potentially reactive chert and cryptocrystalline quartz.

The material removed by washing (about 1 percent by weight) consisted of trace amounts of organic (woody) material and silt containing quartz, feldspar, garnet, amphiboles, magnetite, zircon, apatite, micas, pyrite, and a few miscellaneous minerals. No opal, chert, or cryptocrystalline quartz was detected microscopically in index of refraction immersion oils.

The fine material removed by washing contained no carbonates, trace amounts of chlorides, sulfates, and acid soluble iron oxides. A minor amount of illitic-type clay was observed by clay staining tests.

UNITED STATES GOVERNMENT

# *Memorandum*

Memorandum | Denver, Colorado
---|---
TO : Head, Soil Mechanics Section | DATE: October 4, 1985

FROM : Head, Chemistry, Petrography, and Chemical Engineering Section

SUBJECT: Petrographic Examination of Bonny Dam Loess for Use in Roller Compacted Concrete - Soil-Cement Research - DR-400

Examined by: G. J. Sheldon

Petrographic referral code: 85-81

## INTRODUCTION

(No. 23J-4)

A sample identified as Bonny Dam Loess (No. 23J-2) was submitted for T. Casias, Soil Mechanics Section, to the Petrographic Laboratory for examination. The purpose of the examination was to determine the mineralogical composition and estimated volume percentages, with emphasis on clay minerals, and to determine the water-soluble sulfate content by chemical tests for use in roller compacted concrete laboratory research studies.

## PETROGRAPHIC EXAMINATION

The sample was examined megascopically, microscopically, by X-ray diffraction analyses, and by a few qualitative physical and chemical tests.

The submitted sample consisted of chiefly unconsolidated silt-to clay-size grains with a few soft, highly absorptive, poorly consolidated peds to about 3.5 cm in diameter; was yellowish gray to grayish orange and highly effervescent with dilute hydrochloric acid; and contained numerous dried wood and grass fragments.

The mineralogical composition and estimated volume percentages are listed on the attached table 1. The examined sample contained about 5 to 10 percent mixed-layer smectite, 5 to 10 percent illite/mica, and 2 to 3 percent kaolinite.

Tests performed in the Chemistry Laboratory by B. Frost indicate the presence of less than 0.10 percent water-soluble sulfate in the examined sample.

T. E. Backstrom

Attachment

Copy to: D-230
D-842B
D-1511
D-1523B
D-1541
D-1542 (Casias)
D-1600
D-3300

Table 1. - Mineralogical composition and estimated volume percentages - Sample No. 23J-2 - Bonny Dam Loess - Soil-Cement Research - DR-400

| Mineralogy | Percentages |
|---|---|
| Quartz | 45-50 |
| Clay minerals | |
| Mixed-layer smectite 1/ | 5-10 |
| Illite/mica 2/ | 5-10 |
| Kaolinite | 2-3 |
| Feldspar | 10 |
| Volcanic glass | 10 |
| Calcite | 5 |
| Dolomite | 2-3 |
| Amphibole | 2-3 |
| Minor 3/ | 5 |

1/ Includes minor calcium montmorillonite.
2/ Chiefly illite with minor biotite.
3/ Includes chlorite, hematite, magnetite, ilmenite (?), apatite, and unidentified accessory and clay-size minerals.

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UNITED STATES GOVERNMENT

# Memorandum

Memorandum — Denver, Colorado

TO : Head, Concrete Section — DATE: January 6, 1986

FROM : Head, Chemistry, Petrography, and Chemical Engineering Section

SUBJECT: Petrographic Examination of Clear Creek Aggregate - Denver Office - U.S. Bureau of Reclamation

Examined by: C. A. Bechtold

Petrographic referral code: 85-113

Material: Processed gravel and sand

Source:

| Sample No. | Location |
|---|---|
| M-7726 | Brannan's Pit No. 10, at 63 and Bryant Street, Westminster, Colorado |
| M-7727 | Mobile Pre-Mix crane pit one-half mile west of McIntyre Street on 44th Avenue, Golden, Colorado |

## CONCLUSIONS

Sample No. M-7726

The examined gravel is petrographically of fair physical quality, if used as concrete aggregate, due to the presence of about 1 percent physically poor and 37 percent physically fair quality primarily granite particles.

The gravel contains about 15 percent flat and/or elongated particles which are not considered deleterious to the physical quality of concrete.

No coated particles were observed in the examined sample.

The examined sand is petrographically of satisfactory physical quality, if used as concrete aggregate, due to the presence of only about 3 percent physically poor quality particles in the coarse sand.

The examined gravel and sand are not considered potentially deleteriously reactive with high alkali cement due to the presence of only about 1 percent potentially alkali-reactive chert particles in both the examined gravel and coarse sand.

Qualitative chemical tests indicate the absence of water-soluble chloride and sulfate ions in the examined sand.

Sample No. M-7727

The examined gravel and sand are petrographically of satisfactory physical quality, if used as concrete aggregate, due to the presence of only about 4 percent physically poor and 26 percent physically fair quality primarily granite particles in the gravel and only about 4 percent physically poor quality particles in the coarse sand.

The gravel contains about 15 percent flat and/or elongated particles which are not considered deleterious to the physical quality of concrete.

No coated particles were observed in the examined sample.

The examined gravel and sand are not considered potentially deleteriously reactive with high alkali cement due to the absence of alkali-reactive rock types in the examined gravel and the presence of less than 1 percent potentially alkali-reactive chert particles in the examined coarse sand.

Qualitative chemical tests indicate the absence of water-soluble chloride and sulfate ions in the examined sand.

## SUMMARY

Sample No. M-7726

The gravel, primarily subangular to angular in shape with about 15 percent flat and/or elongated and no coated particles, is composed primarily of granite and gneiss with lesser amounts of pegmatite, altered volcanics, schist, vein quartz, quartzose sandstone, basalt, epidote rock, and chert. About 1 percent physically unsound material and 1 percent potentially alkali-reactive chert particles are present.

The sand, subrounded to angular in shape, is composed of decreasing amounts of rock types found in the gravel and increasing amounts of monomineralic grains of quartz, feldspar, amphibole, sillimanite, mica, chlorite, garnet, sphene, zircon, and magnetite with a few miscellaneous detrital minerals in the finer sizes. About 3 percent physically unsound material and 1 percent potentially alkali-reactive chert particles are present in the coarse sand.

Sample No. M-7727

The gravel, primarily subangular to angular in shape with about 15 percent flat and/or elongated and no coated particles, is composed primarily of granite and gneiss with lesser amounts of pegmatite, altered volcanics, schist, vein quartz, quartzose sandstone, basalt, and epidote rock. About 4 percent physically unsound material and no potentially alkali-reactive rock types are present.

The sand, subrounded to angular in shape, is composed of decreasing amounts of the rock types found in the gravel and increasing amounts of monomineralic grains of quartz, feldspar, amphibole, sillimanite, mica, chlorite, garnet, sphene, zircon, and magnetite with a few miscellaneous detrital minerals in the finer sizes. About 4 percent physically unsound material and less than 1 percent potentially alkali-reactive chert particles are present in the coarse sand.

T. E. Backstrom

Attachments

Copy to: D-842B
D-1523B
D-1542 (Terry Casias)
(with attachments to each)

Table 1. - Petrographic Examination of Coarse Aggregate
Samples No. M-7726 and M-7727

| Rock types | Description of rock types | Physical quality | M-7726 Percentage by particle count | | M-7727 Percentage by particle count | |
|---|---|---|---|---|---|---|
| | | | 37.5 mm to 19 mm | 19 mm to 9.5 mm | 37.5 mm to 19 mm | 19 mm to 9.5 mm |
| Granite | Hard; dense; structureless; fine to medium grained; pink to gray; includes few quartz monzonites | Satisfactory | 35.0 | 38.0 | 45.0 | 45.0 |
| | Somewhat softened and weathered; some fractured | Fair | 25.0 | 27.0 | 21.0 | 18.0 |
| | Soft; porous; absorptive; friable | Poor | 0.5 | 1.0 | 2.0 | 2.0 |
| Gneiss | Hard; dense; gneissic; fine to medium grained; gray; chiefly granite gneiss | Satisfactory | 19.0 | 14.0 | 11.0 | 17.0 |
| | Somewhat softened and weathered; some fractured | Fair | 6.0 | 8.0 | 6.0 | 3.0 |
| | Soft; porous; absorptive; friable | Poor | - | - | 2.0 | 0.5 |
| Pegmatite | Hard; dense; structureless; coarse grained; pink or white; includes few quartz grains | Satisfactory | 2.0 | 1.0 | 1.0 | 1.0 |
| | Somewhat softened and weathered; some fractured | Fair | 1.0 | 0.5 | 1.0 | 1.0 |
| Altered volcanics | Hard; dense; porphyritic; altered aphanitic groundmass; gray; includes rhyolite and andesite | Satisfactory | 2.0 | 0.5 | 3.0 | 2.0 |
| | Somewhat softened and weathered; some fractured | Fair | 0.5 | - | 0.5 | - |
| Schist | Hard; dense; schistose; medium to fine grained; includes mica, amphibolite, and sillimanite schist | Satisfactory | 2.0 | 1.0 | 3.0 | 4.0 |
| | Somewhat softened and weathered; some fractured | Fair | 1.0 | 0.5 | 0.5 | 1.0 |
| | Soft; porous; absorptive; friable | Poor | - | - | - | - |

Table 1. - Petrographic Examination of Coarse Aggregate
Samples No. M-7726 and M-7727 - Continued

| Rock types | Description of rock types | Physical quality | M-7726 Percentage by particle count 37.5 mm to 19 mm | M-7726 Percentage by particle count 19 mm to 9.5 mm | M-7727 Percentage by particle count 37.5 mm to 19 mm | M-7727 Percentage by particle count 19 mm to 9.5 mm |
|---|---|---|---|---|---|---|
| Vein quartz | Hard; dense; coarse grained; white on pink; clear | Satisfactory | 1.0 | 3.0 | 0.5 | 1.0 |
| | Somewhat softened and weathered; some fractured | Fair | 0.5 | 0.5 | - | - |
| Quartzose sandstone | Hard; dense; structureless; fine to medium grained; white to black; silica cemented | Satisfactory | 1.0 | 2.0 | 1.0 | 2.0 |
| | Somewhat softened and weathered; some fractured | Fair | - | 1.0 | - | 0.5 |
| Basalt | Hard; dense; structureless; some vesicular; fine grained; black | Satisfactory | 2.0 | - | 1.0 | 1.0 |
| | Somewhat softened and weathered; some fractured | Fair | 0.5 | 0.5 | 0.5 | - |
| | Soft; porous; absorptive; friable | Poor | - | - | 0.5 | - |
| Epidote rock | Hard; dense; structureless; medium grained; green | Satisfactory | - | - | 0.5 | 1.0 |
| | Somewhat softened and weathered; some fractured | Fair | 0.5 | - | - | - |
| Chert * | Hard; dense; structureless; chalcedonic; white, red, or black | Satisfactory | 0.5 | 1.0 | - | - |
| | Somewhat softened and weathered; some fractured | Fair | - | 0.5 | - | - |

* Alkali-reactive rock types.

Table 2. - Summary of quality of coarse aggregate
Samples No. M-7726 and M-7727

| | | M-7726 | | M-7727 | |
|---|---|---|---|---|---|
| | | Percentage by particle count | | Percentage by particle count | |
| | | 37.5 mm to 19 mm | 19 mm to 9.5 mm | 37.5 mm to 19 mm | 19 mm to 9.5 mm |
| Physical quality | Satisfactory | 64.5 | 60.5 | 66.0 | 74.0 |
| | Fair | 35.0 | 38.5 | 29.5 | 23.5 |
| | Poor | 0.5 | 1.0 | 4.5 | 2.5 |
| Chemical quality | Alkali reactive | 0.5 | 1.5 | - | - |

Remarks:

The particles are essentially subangular to angular with about 15 percent flat and/or elongated in shape.

No coated particles were observed.

The 4.75-mm-size material appears lithologically, physically, and chemically similar to the 19-mm to 9.5-mm-size fraction.

Table 3. - Petrographic examination of coarse sand
Samples No. M-7726 and M-7727

| Rock and mineral types | M-7726 Percentage by particle count | | | M-7727 Percentage by particle count | | |
|---|---|---|---|---|---|---|
| | 2.36 mm | 1.18 mm | 600 µm | 2.36 mm | 1.18 mm | 600 µm |
| Granite | 60 | 55 | 29 | 55 | 50 | 41 |
| Gneiss - chiefly granite gneiss | 13 | 4 | - | 28 | 11 | 10 |
| Altered volcanics - includes rhyolite and andesite | 3 | 4 | 1 | 5 | 8 | 2 |
| Schist - includes mica, amphibolite, and sillimanite schist | 2 | 1 | - | 1 | 1 | 1 |
| Vein quartz and quartz grains | 13 | 25 | 58 | 3 | 14 | 35 |
| Quartzose sandstone | 3 | 1 | - | 1 | Trace | - |
| Basalt | 2 | Trace | - | 1 | 2 | 1 |
| Epidote grains | - | - | 1 | - | - | - |
| Chert | 1 | 1 | Trace | Trace | 1 | - |
| Feldspar grains | 3 | 8 | 9 | 5 | 12 | 8 |
| Mica flakes | - | Trace | Trace | - | Trace | - |
| Amphibole grains | - | 1 | 2 | 1 | 1 | 2 |
| Percent unsound | 4 | 3 | 1 | 5 | 4 | 2 |
| Percent alkali reactive | 1 | 1 | Trace | Trace | 1 | - |
| Percent flat and/or elongated | 13 | * | * | 11 | * | * |
| Percent coated | - | * | * | - | * | * |

* Not determined

Remarks: The coarse sands are subrounded to angular in shape.

The fine sands are angular in shape and composed of decreasing amounts of the rock types found in the coarse sand and increasing amounts of monomineralic grains of quartz, feldspar, amphibole, sillimanite, mica, chlorite, garnet, sphene, zircon, and magnetite with a few miscellaneous detrital minerals. The fine sands contain about 1 percent physically unsound material and a trace of potentially alkali-reactive chert particles.

The material removed by washing, about 4 percent, by weight, in both samples consists of quartz, mica, feldspar, a few miscellaneous detrital minerals, and a trace of carbonaceous material.

Qualitative chemical tests indicate the absence of water-soluble chloride and sulfate ions in the examined sands.

# APPENDIX C

## Mold and Compactor Modifications Drawing

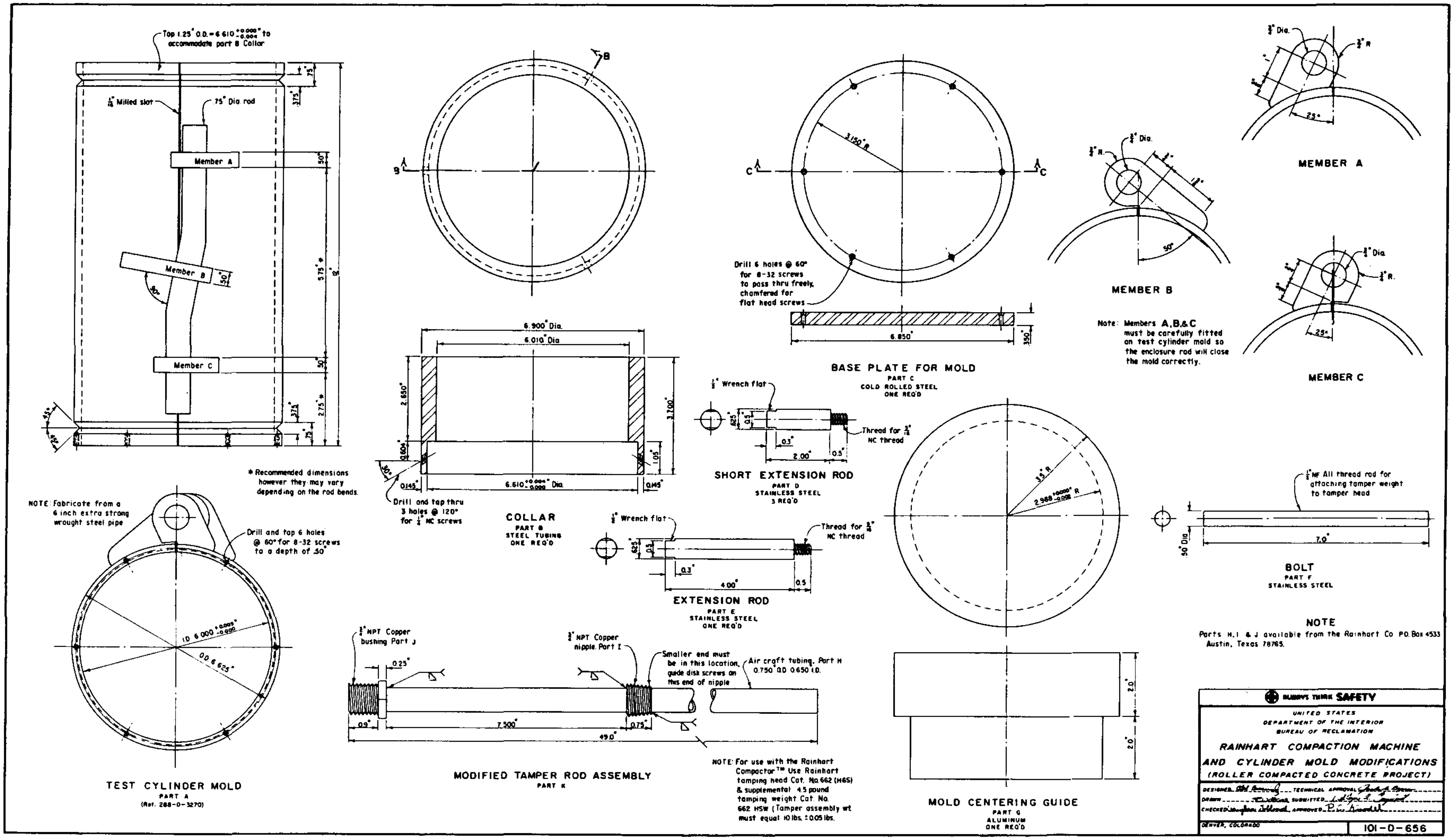


Figure C1.–Rainhart compaction machine and cylinder mold modifications. 101-D-656.

# APPENDIX D

## Laboratory Test Data

| Identification | | | | Laboratory compaction test | | | | Average compressive strength | | | | | Average durability mass loss | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fines content (%) | Number of blows/lift | Compactive effort (ft-lbf/in$^3$) | Compactive effort (ft-lbf/ft$^3$) | Wet unit weight at max. unit weight (lbf/ft$^3$) | Maximum dry unit weight (lbf/ft$^3$) | Calculated optimum moisture content (%) | Water cementitious materials ratio | 7-day (lbf/in$^2$) | 28-day (lbf/in$^2$) | 90-day (lbf/in$^2$) | 180-day (lbf/in$^2$) | 360-day (lbf/in$^2$) | Freeze-thaw (%) | Wet-dry (%) |
| 0 | 27 | 7.2 | 12,442 | 151.7 | 143.4 | 5.8 | 0.64 | 815 | 1,495 | 3,025 | 3,525 | 4,134 | 0.4 | 0.6 |
| | 50 | 13.3 | 22,982 | 152.6 | 145.2 | 5.1 | 0.56 | 1,035 | 1,785 | 2,685 | 4,300 | 4,289 | 0.4 | 0.4 |
| | 80 | 21.2 | 36,634 | 153.4 | 146.5 | 4.7 | 0.51 | 1,400 | 1,980 | 3,245 | 3,830 | 4,600 | 0.4 | 0.2 |
| | 122 | 32.4 | 55,987 | 153.6 | 146.8 | 4.6 | 0.50 | 1,555 | 2,160 | 3,330 | 4,150 | 4,274 | 0.4 | 0.3 |
| 10 | 27 | 7.2 | 12,442 | 149.4 | 139.8 | 6.9 | 0.79 | 690 | 1,165 | 2,555 | 3,110 | 3,272 | 1.2 | 0.3 |
| | 50 | 13.3 | 22,982 | 150.6 | 141.8 | 6.2 | 0.69 | 895 | 1,385 | 3,010 | 3,010 | 3,845 | 0.6 | 0.2 |
| | 80 | 21.2 | 36,634 | 149.8 | 142.7 | 5.0 | 0.56 | 1,070 | 1,605 | 2,925 | 2,850 | 3,678 | 0.6 | 0.4 |
| | 122 | 32.4 | 55,987 | 151.1 | 144.6 | 4.5 | 0.49 | 1,260 | 1,870 | 2,635 | 3,460 | 3,428 | 0.6 | 0.1 |
| 20 | 27 | 7.2 | 12,442 | 146.0 | 136.3 | 7.1 | 0.84 | 470 | 1,015 | 1,890 | 2,300 | 2,688 | 0.5 | 0.6 |
| | 50 | 13.3 | 22,982 | 146.7 | 137.9 | 6.4 | 0.76 | 640 | 1,170 | 1,730 | 2,100 | 2,918 | 0.4 | 1.0 |
| | 80 | 21.2 | 36,634 | 147.3 | 139.0 | 6.0 | 0.70 | 705 | 1,210 | 1,935 | 2,175 | 2,885 | 0.4 | 1.4 |
| | 122 | 32.4 | 55,987 | 148.6 | 141.3 | 5.2 | 0.59 | 985 | 1,475 | 2,305 | 2,520 | 2,991 | 0.6 | 0.9 |

Table D-1.–Summary of roller-compacted concrete test results (compaction, compressive strength, and durability).

| IDENTIFICATION | | LABORATORY COMPACTION TEST | | | INDEX UNIT WEIGHT TESTS | | | | CONCRETE CONSISTENCY TEST 1/ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fines content (%) | Number of blows/lift | Wet unit weight (lbf/ft$^3$) | Max. dry unit weight (lbf/ft$^3$) | Calculated optimum moisture content (%) | Min. index unit weight (lbf/ft$^3$) | Max. index unit weight (dry method) (lbf/ft$^3$) | Max. index unit weight (wet method) (lbf/ft$^3$) | Wet unit weight from max. index unit weight (wet method) (lbf/ft$^3$) | Wet unit weight (lbf/ft$^3$) | Dry unit weight (lbf/ft$^3$) | Water-cementitious materials ratio | Approx. time of consistency test (sec) |
| 0 | 27 | 151.7 | 143.4 | 5.8 | 120.8 | 144.2 | 142.3 | 150.4 | 154.0 | 145.7 | 0.64 | 60 |
| | 50 | 152.6 | 145.2 | 5.1 | | | 146.7 | 154.2 | 153.2 | 145.8 | 0.56 | 180 2/ |
| | 80 | 153.4 | 146.5 | 4.7 | | | 140.3 | 146.9 | 151.5 | 144.7 | 0.51 | 180 2/ |
| | 122 | 153.6 | 146.8 | 4.6 | | | 140.5 | 147.0 | 151.7 | 145.0 | 0.50 | 180 2/ |
| 10 | 27 | 149.4 | 139.8 | 6.9 | 120.1 | 143.9 | 145.7 | 155.6 | 150.9 | 141.3 | 0.79 | 30 |
| | 50 | 150.6 | 141.8 | 6.2 | | | 145.0 | 153.7 | 151.3 | 142.7 | 0.69 | 60 |
| | 80 | 149.8 | 142.7 | 5.0 | | | 131.9 | 138.5 | 150.1 | 143.0 | 0.56 | 180 2/ |
| | 122 | 151.1 | 144.6 | 4.5 | | | 126.3 | 132.0 | 144.1 | 137.9 | 0.49 | 180 2/ |
| 20 | 27 | 146.0 | 136.3 | 7.1 | 117.9 | 141.1 | 136.7 | 146.4 | 147.7 | 137.9 | 0.84 | 30 |
| | 50 | 146.7 | 137.9 | 6.4 | | | 128.7 | 137.1 | 145.7 | 136.8 | 0.76 | 180 2/ |
| | 80 | 147.3 | 139.0 | 6.0 | | | 128.2 | 135.9 | 145.7 | 137.5 | 0.70 | 180 2/ |
| | 122 | 148.6 | 141.3 | 5.2 | | | 115.7 | 121.7 | 143.1 | 136.0 | 0.59 | 180 2/ |

1/ Tests performed on RCC mixes prepared at the approximate optimum moisture contents determined from RCC laboratory compaction tests.
2/ Mortar ring did not form, vibration was stopped and time recorded.

Table D-2.–Summary of roller-compacted concrete index unit weight and concrete consistency test results.

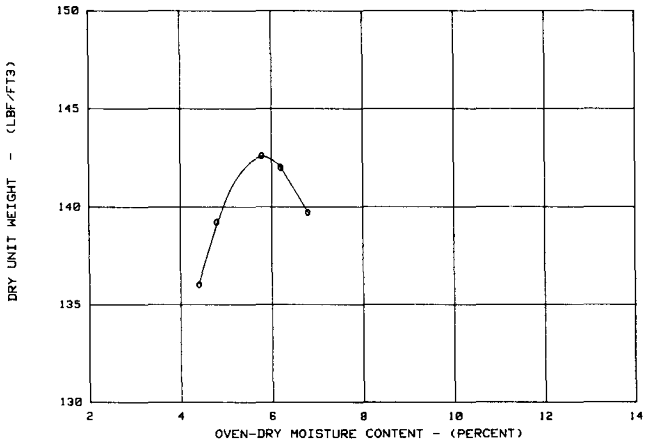


Figure D1.-Compaction curve — aggregate with 10% fines (27 blows per lift).

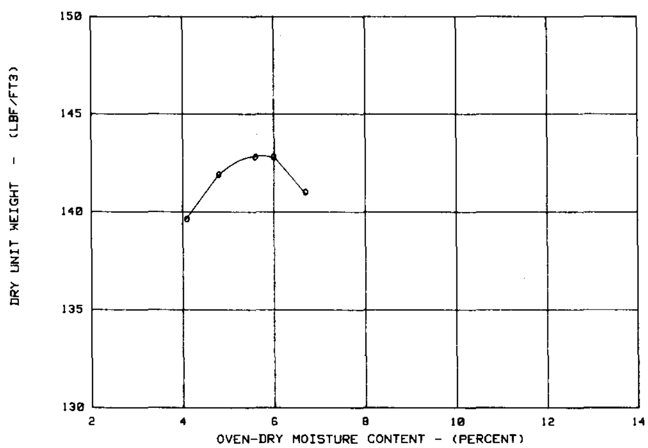


Figure D2.-Compaction curve — aggregate with 10% fines (50 blows per lift).

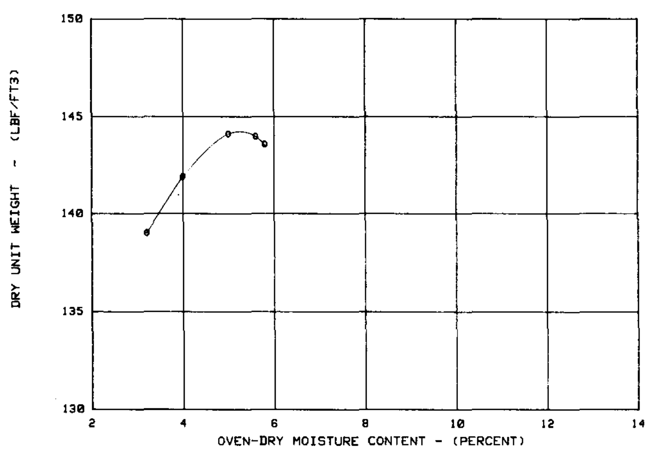


Figure D3.-Compaction curve — aggregate with 10% fines (80 blows per lift).

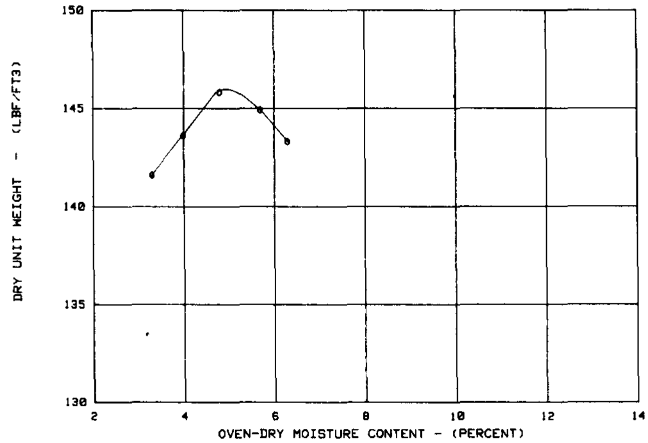


Figure D4.-Compaction curve — aggregate with 10% fines (122 blows per lift).

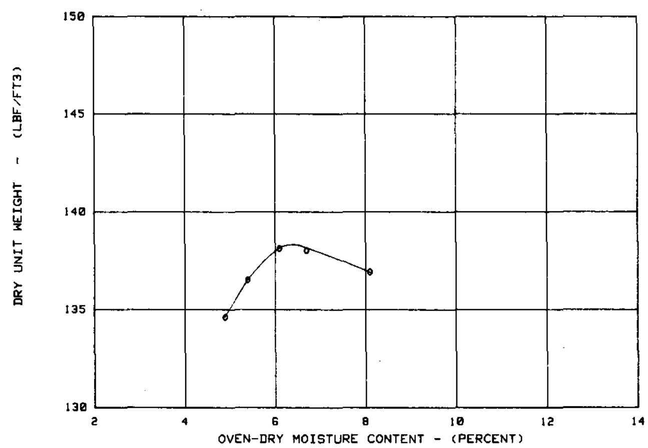


Figure D5.-Compaction curve — aggregate with 20% fines (27 blows per lift).

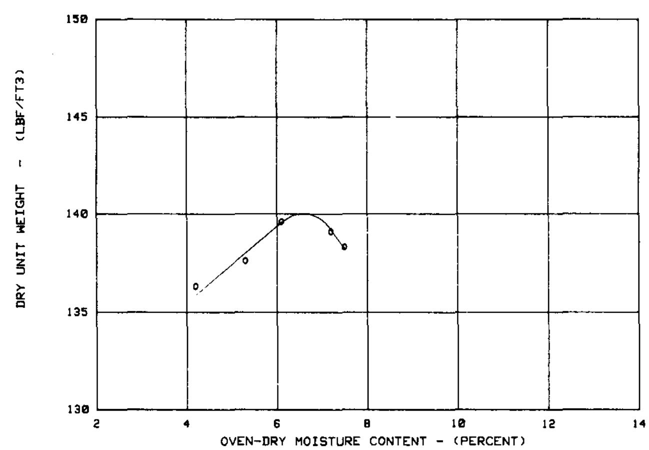


Figure D6.-Compaction curve — aggregate with 20% fines (50 blows per lift).

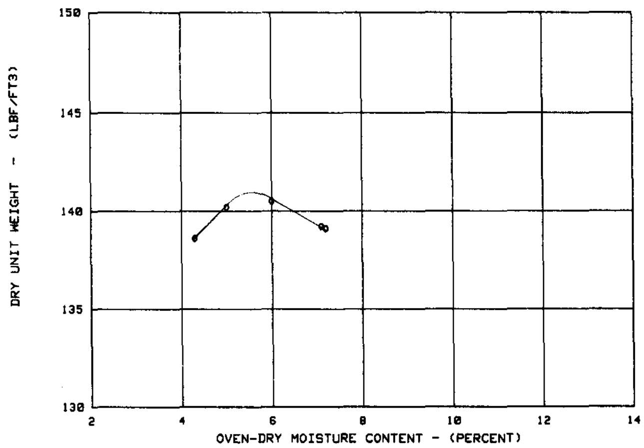


Figure D7.–Compaction curve — aggregate with 20% fines (80 blows per lift).

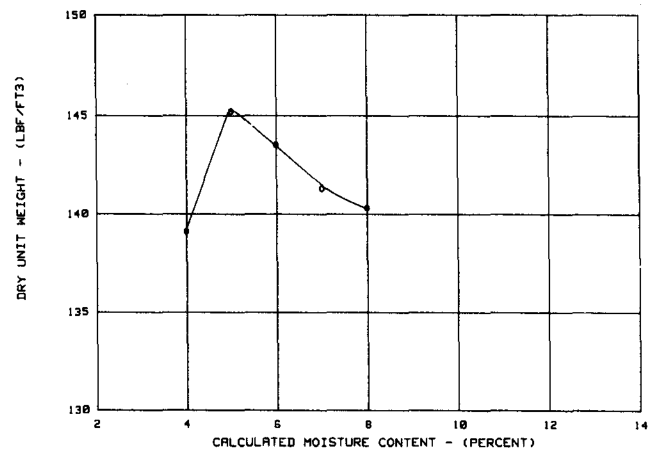


Figure D10.–Compaction curve — roller-compacted concrete (0% fines, 50 blows per lift).

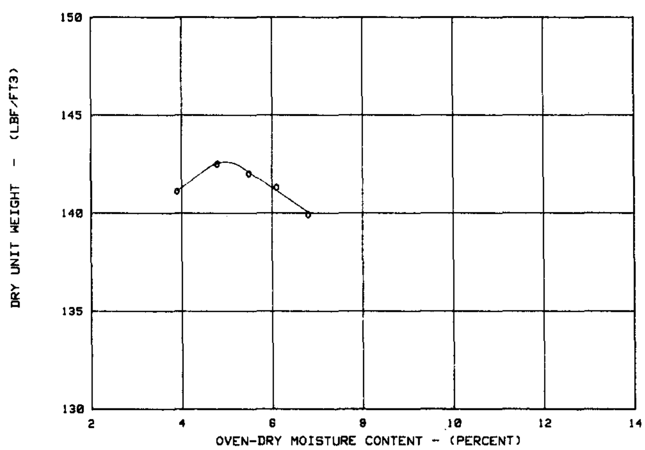


Figure D8.–Compaction curve — aggregate with 20% fines (122 blows per lift).

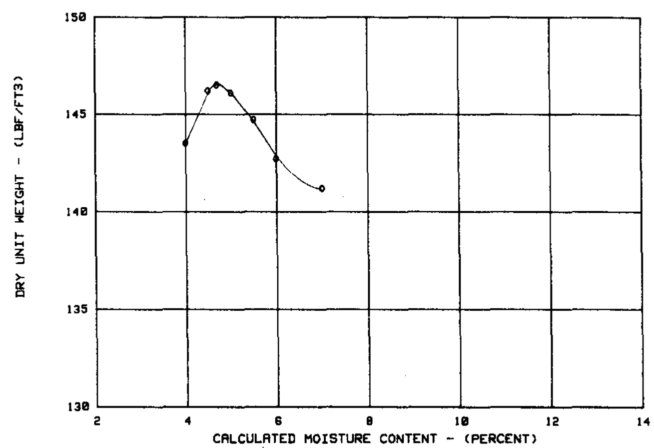


Figure D11.–Compaction curve — roller-compacted concrete (0% fines, 80 blows per lift).

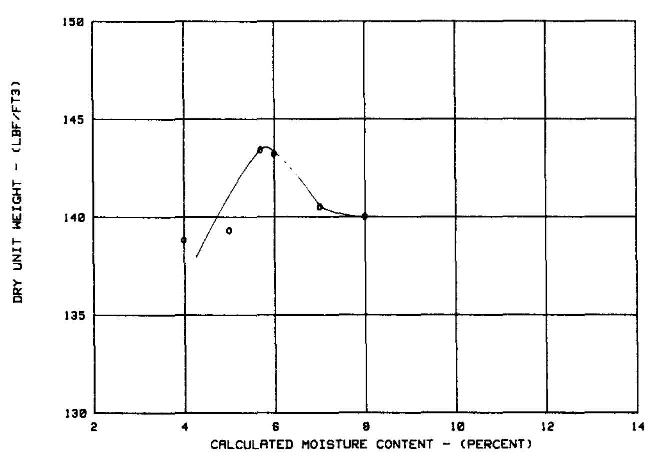


Figure D9.–Compaction curve — roller-compacted concrete (0% fines, 27 blows per lift).

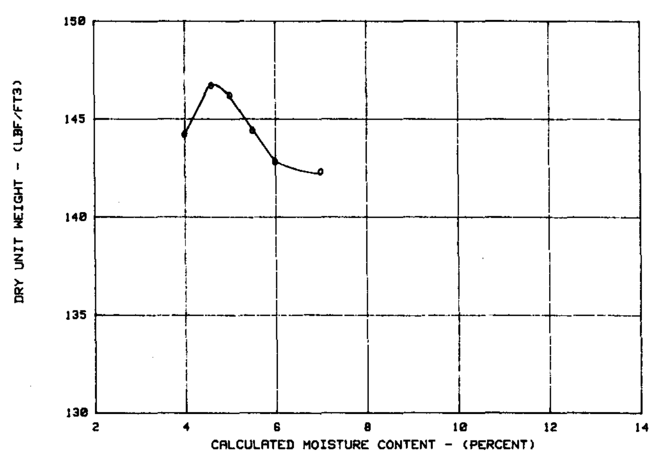


Figure D12.–Compaction curve — roller-compacted concrete (0% fines, 122 blows per lift).

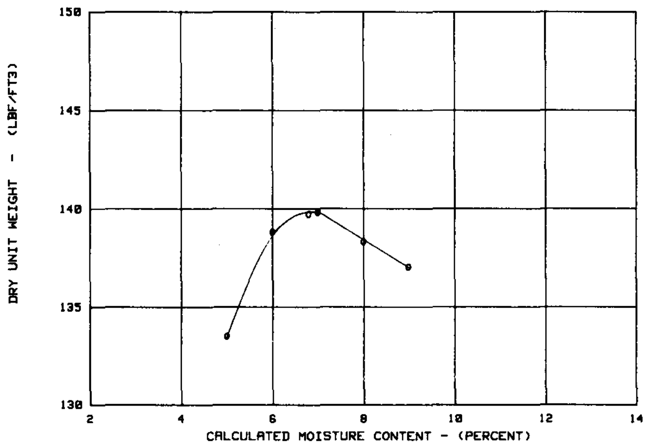


Figure D13.–Compaction curve — roller-compacted concrete (10% fines, 27 blows per lift).

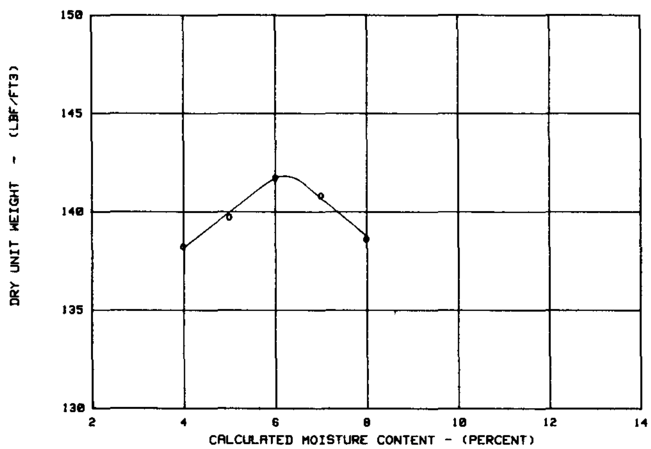


Figure D14.–Compaction curve — roller-compacted concrete (10% fines, 50 blows per lift).

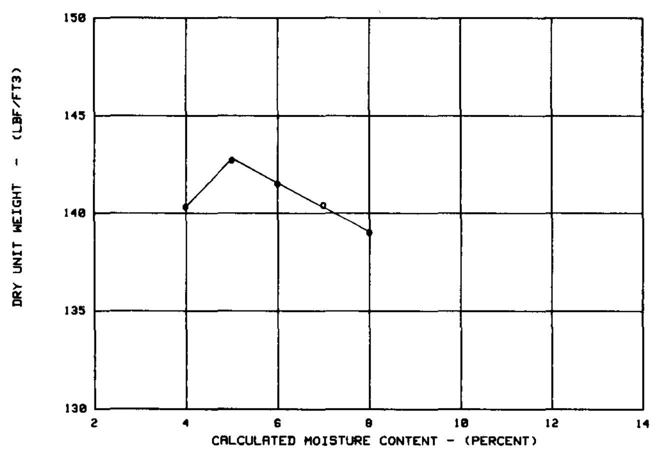


Figure D15.–Compaction curve — roller-compacted concrete (10% fines, 80 blows per lift).

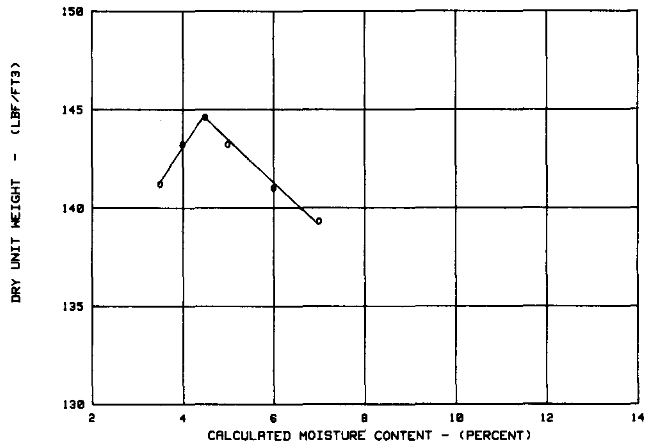


Figure D16.–Compaction curve — roller-compacted concrete (10% fines, 122 blows per lift).

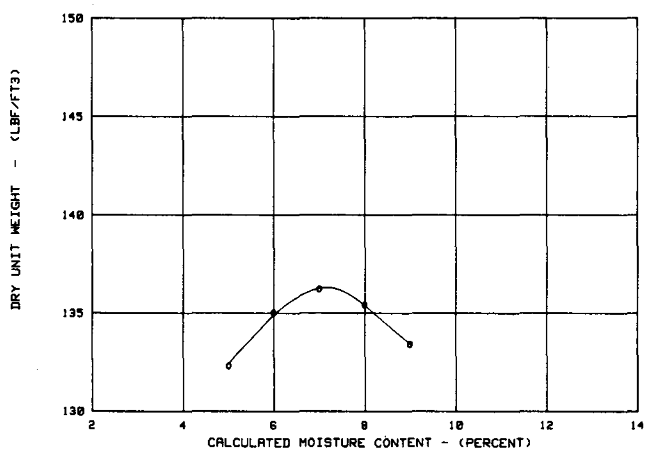


Figure D17.–Compaction curve — roller-compacted concrete (20% fines, 27 blows per lift).

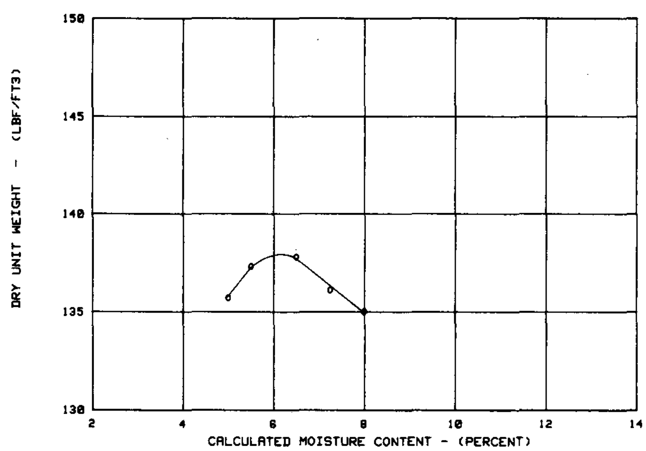


Figure D18.–Compaction curve — roller-compacted concrete (20% fines, 50 blows per lift).

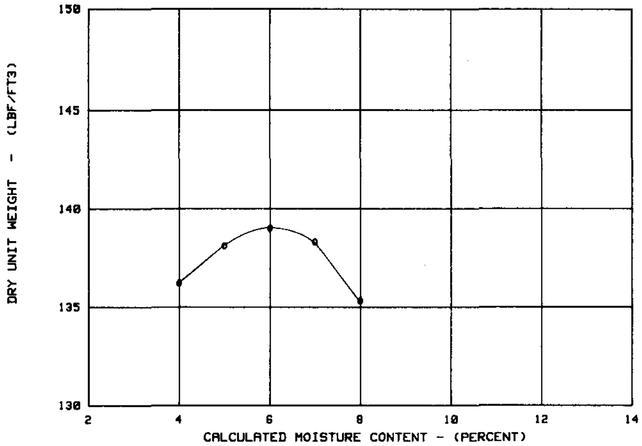


Figure D19.–Compaction curve — roller-compacted concrete (20% fines, 80 blows per lift).

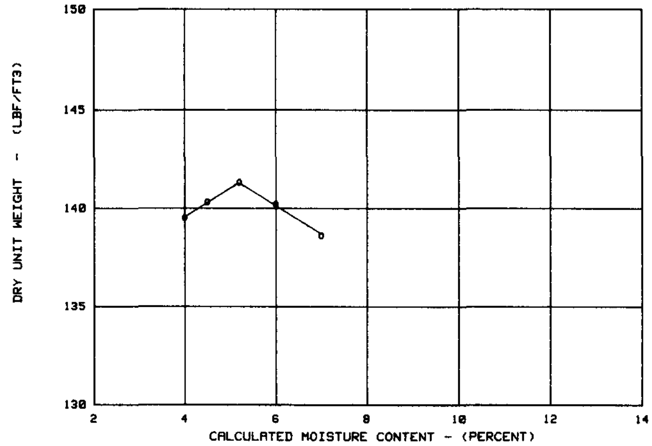


Figure D20.–Compaction curve — roller-compacted concrete (20% fines, 122 blows per lift).

# APPENDIX E

## Laboratory Testing Procedures

## Laboratory Compaction Test - Aggregate With Fines

Sample preparation. - A 0.30-$ft^3$ batch of the required aggregate and fines blend was prepared for each compaction test specimen. The aggregate and fines blend used for each specimen met gradation requirements for the specified RCC mix design, excluding cement, fly ash, and WRA (water reducing agent). The required quantity of water was calculated and added to the aggregate and fines blend and thoroughly mixed by hand. The moistened mixture was covered and set aside for 10 minutes to allow time for dispersion and absorption of the water. Each specimen was mixed, moistened, and compacted individually.

Compaction. - The mass and volume of each compaction mold was predetermined. The assembled mold was placed on the baseplate of the automatic compaction device, centered using the mold centering guide, and secured to the baseplate. Approximately 4.5 to 5.0 lbm of aggregate and fines was placed in the mold and spread into a layer of uniform thickness. The layer was then compacted with the specified number of blows from a 10.0-lbm sector-faced rammer dropped from a height of 18.0 inches. The blows were distributed over the entire surface of the layer. This process was repeated until six layers were compacted. Prior to placement of the sixth layer, the collar of the mold was attached to the mold assembly. The sixth layer, when compacted, extended 0.25 to 0.50 inch into the collar (above the mold). The mold and collar were removed from the baseplate of the compaction device. The collar was removed from the mold; and using a straightedge, the specimen was trimmed flush with the top of the mold. The mass of the mold and compacted wet aggregate and fines blend determined. The wet unit weight of the specimen was calculated. The specimen was extruded from the mold, placed in a suitable container, and the entire specimen used for an ovendry moisture content determination. This procedure was repeated until at least five specimens were compacted at different moisture contents. The dry unit weight of each specimen was calculated using the ovendry moisture content. The ovendry moisture contents versus corresponding dry unit weights were plotted. At least two plotted points were required to fall on either side of optimum moisture content. If not, additional specimens were prepared and compacted at appropriate moisture contents to meet the above requirement.

Laboratory Compaction Test - RCC

Sample preparation. - RCC batches of 0.30 and 0.60 $ft^3$ were prepared for laboratory compaction testing. When practical, enough material to prepare two specimens (0.60 $ft^3$) was mixed at one time. In cases where the time required to compact two specimens was excessive or only one specimen was required, a 0.30-$ft^3$ batch of RCC was prepared. The required quantities of aggregate, sand, fines (when required), cement, fly ash, water, and WRA were batched based on the RCC mix design and desired moisture content. The quantity of water was adjusted based on the absorption of the aggregate and the moisture content of the fines (when required).

The aggregate and approximately one-half of the required water was placed in the mixer and mixed for 1 minute. The cement, fly ash, and fines (when required) were dry mixed separately by hand in a small pan and added to the moist aggregate mixture with the remaining water and WRA. Mixing was continued for 4 minutes. When fines were used, some of the material would stick to the mixer causing segregation. To eliminate this problem, mixing was stopped after 2 minutes, and the inside of the mixer was scraped and the mixing continued for the remaining 2 minutes. Upon completion of mixing, the material was dumped into a large, damp, metal pan and remixed with a trowel to minimize segregation of the coarser material. The material was covered with damp towels to protect the RCC mixture against moisture loss prior to and during the compaction process.

Compaction. - The mass and volume of each compaction mold was predetermined. The assembled mold was placed on the baseplate of the automatic compaction device, centered using the mold centering device, and secured to the baseplate. Approximately 4.5 to 5.0 lbm of RCC was placed in the mold and spread into a layer of uniform thickness. The layer was then compacted with the specified number of blows from a 10-lbm sector-facedrammer dropped from a height of 18.0 inches. The blows were distributed over the entire surface of the layer. The process was repeated until six layers were compacted. Prior to placement of the sixth layer, the collar of the mold was attached to the mold assembly. The sixth layer, when compacted, extended 0.25 to 0.50 inch into the collar (above the mold). The mold and collar were removed from the baseplate of the compaction device. The collar was removed from the mold; and using a straightedge, the specimen was trimmed flush with the top of the mold. The mass of the mold and compacted wet RCC was determined, and the wet unit weight was computed. Because of cement hydration, ovendry moisture content determinations provided erratic results. Therefore, the design moisture content (by dry batch mass) was used to calculate the dry unit weight of each specimen.

This procedure was repeated until at least five specimens were compacted at different moisture contents. The design moisture contents versus corresponding dry unit weights were plotted. At least two plotted points were required to fall on either side of optimum moisture content. If not, additional specimens were prepared and compacted at appropriate moisture contents to meet the above requirement.

## Unconfined Compressive Strength Test

Sample preparation. - Mixes for the RCC compressive strength test specimens were prepared at optimum moisture contents determined from the laboratory compaction procedure. The mixes were prepared in the same manner as described in the compaction test for RCC.

Compaction. - The compressive strength test specimens were compacted in the same manner as the compaction specimens, except that each layer was rodded 25 times with a round-nosed 5/8-inch-diameter tamping rod to ensure that the material was uniformly distributed along the sides of the mold. The specimens were compacted to within ± 0.5 percent of the laboratory maximum dry unit weight, as determined from the laboratory compaction test. Because of the coarse aggregate, the top surface of the specimen was usually rough after trimming; and it was necessary to apply a thin cover using a 3:1 (sand to cement) grout mix to provide a relatively smooth, uniform surface for the sulfur cap. The compressive strength specimens were cured in the mold in a fog room (100 percent humidity) at 73.4 ± 3.0 °F or a period of 24 hours before removal from the mold. The specimens were labeled and placed in the fog room for the remainder of the specified curing period.

Compressive strength testing. - At the end of the specified curing period, the test specimens were capped with sulfur in accordance with Concrete Manual, [5] Designation 32, Capping Concrete Cylinders. The test specimens were loaded in compression to failure in accordance with Concrete Manual, Designation 33, Compressive Strength [5]. Compressive strength was calculated as the load at failure divided by the cross-sectional area.

## Wet-Dry and Freeze-Thaw Durability Tests

Sample preparation. - Mixes for RCC durability test specimens were prepared at the optimum moisture contents determined from the laboratory compaction procedure for RCC. The mixes were prepared in the same manner as described in the compaction test for RCC.

Compaction. - The durability test specimens were compacted in the same manner as the compaction specimens, except that each layer was rodded 25 times with a round-nosed 5/8-inch-diameter tamping rod to ensure that the material was uniformly distributed along the sides of the mold. The specimens were compacted to within

$\pm$ 0.5 percent of the laboratory maximum dry unit weight, as determined in the laboratory compaction test. The durability test specimens were cured in the mold in a fog room (100% humidity) at 73.4 $\pm$ 3.0 °F for a period of 24 hours before removing from the mold. The specimens were labeled and placed in the fog room for the remainder of the 7-day curing period.

Preparation for testing. - Upon completion of the 7-day curing period in the fog room, the 6.0-inch-diameter by 12-inch-high test specimen was cut to a length of 5.77 inches with a masonry saw. The outside of each specimen was taped at the location to be cut prior to cutting to minimize damage to the edges. The moisture content of the specimen was determined from the cut ends of the test specimen. After the ends of the test specimens were cut, the wet mass of each specimen was determined. Using the moisture content obtained from the ends, the initial dry mass of the specimen was calculated.

Wet-dry durability testing. - The remainder of the W-D (wet-dry) durability test was performed in accordance with procedures described in subparagraphs 12.1 through 12.9, 12.12, and 12.13 of USBR 5820, Procedure for Performing Wet-Dry Durability Testing of Compacted Soil-Cement Mixtures.* Because of the larger surface area of the 6-inch-diameter RCC test specimen as compared to the 4-inch-diameter soil-cement test specimen, more brush strokes were required to cover the entire surface area of the RCC specimen. Twenty-two to twenty-four brush strokes were required to cover the

* USBR 5820 will be available in the new edition of the Earth Manual.

sides of the RCC specimen twice, and six strokes were required on each end. This produced approximately the same amount of brushing per unit area as is used on the standard 4-inch-diameter soil-cement specimens.

<u>Freeze-thaw durability testing</u>. - The remainder of the F-T (freeze-thaw) durability test was performed in accordance with procedures described in subparagraphs 13.1 through 13.12, 13.14, and 13.15 of USBR 5825, Procedure for Performing Freeze-Thaw Durability Testing of Compacted Soil-Cement Mixtures.* Because of the larger surface area of the 6-inch-diameter RCC test specimen as compared to the 4-inch-diameter soil-cement test specimen, more brush strokes were required to cover the entire surface area of the RCC specimen. Twenty-two to twenty-four brush strokes were required to cover the sides of the RCC specimen twice, and six strokes were required on each end. This produced approximately the same amount of brushing per unit area as is used on the standard 4-inch-diameter soil-cement specimen.

## Relative Density Test

<u>Sample preparation</u>. - Three types of samples were prepared for relative density testing: dry aggregate only; dry aggregate with and without fines, cement, and fly ash; and aggregate with and without fines, cement, and fly ash with water and WRA added. The dry mixes were prepared by hand, mixing the aggregate with and without fines first and adding cement and fly ash when required

* USBR 5825 will be available in the new edition of the Earth Manual.

immediately prior to testing. The wet mixes were prepared at optimum moisture content as determined from the laboratory compaction procedure, in the same manner as the compaction test specimens.

Testing. - Minimum and maximum index unit weight tests were performed in accordance with the Earth Manual [4], Designation E-12, Relative Density of Cohesionless Soils; except that during maximum index unit weight testing, intermediate dial readings were taken after 30 seconds and after 2 minutes of the total 8 minutes of vibration time.

## Concrete Consistency Test

Sample preparation. - Mixes for consistency tests on RCC were prepared in the same manner as described in the laboratory compaction test on RCC.

Testing. - Using a scoop, the entire 30-lbm specimen of RCC was placed into a 9-1/2-inch-inside-diameter by 8-inch-high mold. The mold was attached to a mechanically driven vibrating table with adjustable eccentrics, calibrated to produce a double amplitude of vibration of 0.020 inch at a frequency of 60 Hz. A 50-lbm surcharge was placed on top of the specimen. The table was activated and the inside edge of the mold observed for formation of a "mortar ring." As soon as the ring formed, vibration was stopped, vibration time recorded, the surcharge removed, and the wet unit weight determined. If, following 3 minutes of vibration, the "mortar ring" had not formed, vibration was stopped, the time recorded, the surcharge removed, and the wet unit weight determined.

The volume of the portion of the mold above the consolidated RCC specimen was determined using the water replacement method. This volume was subtracted from the predetermined total volume of the mold to provide the volume of RCC. Using the initial mass of the RCC and the calculated volume of RCC, the wet density of RCC was determined and converted to wet unit weight.

# APPENDIX F

## Calculations for Determining Length of Roller-Compacted Concrete Durability Test Specimens

## Sample Calculations for Determining Theoretical Zero Air Void Unit Weight and Percent Compaction

## CALCULATIONS FOR DETERMINING LENGTH OF RCC DURABILITY TEST SPECIMENS

The RCC durability test specimens were cut to a length of 5.77 inches to provide the same relationship of maximum aggregate size to surface area as provided by current soil-cement durability testing procedures.

Standard soil-cement durability test specimens are 4 inches in diameter by 4.58 inches high, and a maximum aggregate size of 3/4 inch is allowed. The surface area of a cylindrical specimen is determined using the following equation:

$$SA = 2\pi r\,(h + r)$$

where

$SA$ = Surface area of a cylindrical specimen (in$^2$)

$r$ = Radius of cylinder (in)

$h$ = Height of cylinder (in)

$\pi$ = Con tant equal to 3.1416

Solving for the surface area of a soil-cement specimen (4 inches in diameter by 4.58 inches high):

$$SA_{SC} = 2\pi(2)(4.58 + 2)$$

$$SA_{SC} = 82.69 \text{ in}^2$$

Solving for the surface area of an RCC specimen where the diameter equals 6 inches and the height (h) is unknown:

$h$ = height (in)

$r$ = 3 inches

$$SA_{RCC} = (2)\pi(3)(h + 3)$$

$$SA_{RCC} = 18.85h + 56.55$$

The value of h was then determined using a proportion of required surface area to maximum aggregate size (1-1/2 inches for RCC specimens) as follows:

$$\frac{\text{Surface area of soil-cement specimen}}{\text{Soil-cement maximum aggregate size}} = \frac{\text{Surface area of RCC specimen}}{\text{RCC maximum aggregate size}}$$

$$\frac{82.69}{0.75} = \frac{18.85h + 56.55}{1.50}$$

$$h = 5.77 \text{ inches}$$

## SAMPLE CALCULATIONS FOR DETERMINING THEORETICAL ZERO AIR VOID UNIT WEIGHT AND PERCENT COMPACTION

The following calculations show the procedure for determining theoretical compaction based on theoretical zero air void wet unit weight. The example summarizes calculations for the RCC mix containing 0 percent fines prepared at a moisture content of 5.1 percent (optimum moisture content determined from compaction procedure using 50 blows per lift), figure 17.

From the original mix design (see table 1):

| | |
|---|---|
| Coarse aggregate, SSD mass | 2680.0 lbm |
| Coarse aggregate, dry mass | 2656.8 lbm |
| Absorbed moisture in coarse aggregate (see table 3) | 23.2 lbm |
| Sand, SSD mass | 952.0 lbm |
| Sand, dry mass | 945.0 lbm |
| Absorbed moisture in sand (see table B-1) | 7.0 lbm |
| Total mass of absorbed moisture | 30.2 lbm |

(Absorbed moisture in coarse aggregate) +
(Absorbed moisture in sand) =
(23.2 lbm) + (7.0 lbm)

| | |
|---|---|
| Total mass of free moisture | 164.5 lbm |
| Total mass of water | 194.7 lbm |

(Total free moisture) +
(Total absorbed moisture) =
(164.5 lbm) + (30.2 lbm)

| | |
|---|---|
| Mass of cementitious materials (50% cement + 50% fly ash) | 300.0 lbm |

Total mass of dry material 3901.8 lbm

(Dry mass of coarse aggregate) +
(Dry mass sand) +
(Mass cementitious materials)
(2656.8 lbm + 945.0 lbm + 300 lbm)

Wet mass of RCC 4096.5 lbm

(Total mass of water) +
(Total mass dry material) =
(194.7 lbm) + (3901.8 lbm)

Solid volume of RCC 26.59 ft$^3$

Theoretical wet zero air void unit weight 154.1 lbf/ft$^3$

$$\frac{\text{SSD mass of RCC}}{\text{Solid volume}} = \frac{4096.5 \text{ lbm}}{26.59 \text{ ft}^3}$$

Mix adjusted for 5.1 percent moisture

Wet unit weight at maximum dry unit weight obtained from compaction test is 152.5 lbf/ft$^3$ (fig. 17).

Total mass of water at 5.1 percent moisture 199.0 lbm

(Total dry mass of RCC)(Moisture content) =
(3901.8 lbm)(5.1/100)

Total mass of water-mass of absorbed water 168.8 lbm
(199.0 lbm) - (30.2 lbm)

Mass of additional free water above original mix design 4.3 lbm
(168.8 lbm) - (164.5 lbm)

Volume of additional free water above original mix design 0.07 ft$^3$

$$\frac{\text{Mass of additional water}}{\text{Density of water}} = \frac{4.3 \text{ lbm}}{62.4 \text{ lbm/ft}^3}$$

*Theoretical wet zero air void unit weight 153.8 lbf/ft3

$$\frac{\text{(SSD mass of original RCC mix + mass of additional water)}}{\text{(Solid volume of original RCC mix + volume of additional water)}}$$

$$\frac{(4096.5 \text{ lbm} + 4.3 \text{ lbm})}{(26.59 \text{ ft3} + 0.07 \text{ ft3})}$$

Theoretical percent compaction 99.2 %

$$\frac{\text{(Wet unit weight obtained from compaction test)}}{\text{(Theoretical wet zero air void unit weight)}} \times 100$$

$$\frac{152.6 \text{ lbf/ft}^3}{153.8 \text{ lbf/ft}^3} \times 100$$

*For this application, assume 1 lbm equals 1 lbf.

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