
STATE OF TENNESSEE
DEPARTMENT OF TRANSPORTATION

# TENNESSEE FLOWABLE FILL STUDY

FINAL REPORT

Project Number TNSPR-RES1230

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September 2003

Prepared for:

Tennessee Department of Transportation
In cooperation with
U.S. Department of Transportation
Federal Highway Administration

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**Department of Transportation Authorization # 401341**
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**Technical Report Documentation Page**

| 1. Report No. (TNSPR) RES 1230 | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| 4. Title and Subtitle<br>Tennessee Flowable Fill Study | | 5. Report Date<br>6. Performing Organization Code |
| 7. Author(s) L. K. Crouch, V. James Dotson, Richard Maxwell, Tim R. Dunn, T. Adam Borden and Daniel Badoe | | 8. Performing Organization Report No. |
| 9. Performing Organization Name and Address<br>Center for Electric Power<br>Box 5032, Tennessee Technological University<br>Cookeville, TN 38505-0001 | | 10. Work Unit No. (TRAIS)<br>11. Contract or Grant No.<br>CUT 277 |
| 12. Sponsoring Agency Name and Address<br>Materials and Tests Division<br>Tennessee Department of Transportation<br>6601 Centennial Blvd. Nashville, TN 37243-0360 | | 13. Type of Report and Period Covered<br>August 1, 2002 to August 31, 2003<br>14. Sponsoring Agency Code |
| 15. Supplementary Notes | | |

16. Abstract


A study of Controlled Low-Strength Material (CLSM) was conducted in two parts: Excavatable flowable fill (EFF) and ZOOM! CLSM;

**EFF**

Twenty-three different EFF mixtures were placed in trenches simulating utility cuts during March through May of 2001. All EFF mixtures were tested for flow, unit weight, gravimetric air content, suitability for load application, and compressive strength development over time. The trenches were excavated in March 2003.

Nine EFF mixtures were used to access the impact of Portland cement content and ASTM C 618 Class F fly ash content. Portland cement contents of 30, 45, and 60 lbs/CY and ASTM C 618 Class F fly ash contents of 300, 370, and 440 lbs/CY were used to evaluate the impact of component proportions. PC-F Ash EFF mixtures with cementitious materials contents between 415 and 500 lbs/CY were found to have a high probability of having an ASTM D 6103 flow greater than 8-inches and passing the ASTM D 6024 ball drop test in less than 24 hours. In addition, the PC content of PC-Class F fly ash EFF mixtures appears to be more important to early compressive strength development. Further, strong relationships exist between component material proportions and 28-day and maximum compressive strengths and excavation difficulty.

Six EFF mixtures were used to access the impact of Portland cement content and high-unburned carbon fly ash content. Portland cement contents of 45 and 60 lbs/CY and high-unburned carbon fly ash contents of 370, 440, 510 lbs/CY were used to evaluate the impact of component proportions. The use of high carbon ash typically extended the time required to pass the ball drop test and often generated some erratic strength results. Therefore, the research team was hesitant to recommend the use of mixtures containing high carbon ash without further research.

The influence of aggregate type on EFF mixtures was evaluated by using five different aggregate types in the EFF mixture recommended by TRMCA (45 lbs/CY Portland cement and 370 lbs/CY ASTM C 618 Class F fly ash). Unfortunately, the previously mentioned strong relationships between component material proportions and 28-day and maximum compressive strengths and excavation difficulty appear to be aggregate dependent. In addition, very uniform fine aggregates were found to be likely to produce EFF mixtures that bleed excessively and are prone to segregation and flow problems. Further, limestone screenings produced the highest 28-day and maximum compressive strengths and river sand produced the lowest 28-day and maximum compressive strengths in PC-F Ash EFF mixtures.

Four comparison EFF mixtures were also used in the study (1 TDOT and 3 air-entrained EFF mixtures). There appears to be an excellent relationship between compressive strength of air-entrained EFF mixtures and excavation difficulty. Further, air-entrained EFF mixtures are easier to excavate at the same compressive strength than non-air-entrained PC-Class F fly ash EFF mixtures. Finally, the Excavation Index (EI) combines the effects of compressive strength and density to predict excavatability. EFF mixtures with EI less than 10.0 are excavatable with a Case 580E backhoe.

**ZOOM! CLSM**

A high-flow, rapid-set, non-excavatable controlled low-strength material (flowable fill) was developed for applications where time was critical. The mixture was required to be ready for load application in six hours regardless of subgrade moisture conditions and uses materials commonly available at ready mix facilities. Further, the mixture, called ZOOM!, must be able to tolerate a wide variety of Tennessee fine aggregates types including Ohio River sand, manufactured limestone sand, limestone screenings, and crushed sandstone.

An initial ZOOM! mixture was produced using Ohio River sand. Subsequently, the mixture proportions were adjusted to produce the desired plastic and hardened properties with other Tennessee fine aggregates. Laboratory work and three successful field demonstrations indicated that fine aggregate properties such as gradation and angularity dictate mixture proportions required to achieve flow, air content, and bleeding characteristics of ZOOM! CLSM. Average air temperature was found to be indirectly proportional to time of suitability for load application. ZOOM! CLSM air content was found to be directly proportional to time of suitability for load application.


| 17. Key Words | | 18. Distribution Statement |
|---|---|---|
| CLSM | compressive strength | |
| backfill | ball drop apparatus | |
| excavatability | flow consistency | |
| air content | fine aggregate | |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price |
|---|---|---|---|
| Unclassified | Unclassified | 106 | |

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## BACKGROUND

The Combustion By-Products Recycling Consortium (CBRC), Tennessee Ready Mixed Concrete Association, and Kentucky Ready Mixed Concrete Association began a study of excavatable flowable fill (EFF) in 2001. CBRC funding was reduced by the US Department of Energy due to increases in spending for homeland defense. Subsequently, CBRC decided not to fund the second year of the TTU EFF study. The Tennessee Department of Transportation Materials and Tests Division agreed to continue the project as primary sponsor beginning in August 2002.

The American Concrete Institute Committee 229 (1) defines controlled low strength material (CLSM) as a self-compacted, cementitious material used primarily as backfill having a compressive strength of 1200-psi or less. CLSM is commonly referred to as flowable fill. Flowable fill component proportions and resulting compressive strength are a function of the desired application. Flowable fills with strengths less than approximately 150-psi are termed excavatable and are primarily used as utility cut backfills. Flowable fills in the range of 150 to 1200-psi are used as structural fills, pavement base materials, or as a working platform.

The wide scope of TDOT operations encompasses applications for both EFF and non-excavatable flowable fill. Therefore, the study was conducted in two parts: First, the EFF study initiated by CBRC, TRMCA, and KRMCA continued with TDOT replacing CBRC as primary sponsor. Second, a high flow, rapid setting CLSM to serve as a working platform and/or structural fill was developed. Due to the dual approach used in the Tennessee Flowable Study, the final report is divided into two sections: the first on EFF and a second section on ZOOM! CLSM.

## EXCAVATABLE FLOWABLE FILL

### EFF Introduction

Excavatable flowable fill (EFF) is a blend of Portland cement, fine aggregate, water, and admixtures. EFF is delivered in a ready mix truck, but EFF is not concrete. EFF was developed to serve as an alternate backfill for roadway utility cuts. The three primary advantages of EFF are:

1) Improved worker safety – requires no compaction, therefore workers spend less time in the utility trench
2) No in-service settlement – utility cut patches do not sink producing roadway hazards
3) Can be removed with conventional excavating equipment – no jack hammering

Unlike Portland cement concrete (PCC), higher compressive strength is not beneficial for EFF. PCC requires a minimum strength to perform properly in structures. EFF requires both a minimum and maximum strength to perform properly. Minimum strength recommendations are to assure that EFF has adequate bearing capacity and does not settle (deform) excessively under load. Maximum strength recommendations are to assure that EFF can be removed with conventional excavating equipment.

### EFF Research Significance

EFF mixture design requires a new mindset. The "stronger is better" idea does not work with EFF. Several well-meaning designers have produced "EFF" mixtures, which are not excavatable using the "stronger is better" idea. The paste portion of the mixture

(Portland cement, water, air, and admixtures) is critical to EFF performance. Proper paste proportions allow EFF mixtures to be fluid, develop adequate early strength, and yet not become so strong that it cannot be excavated later. The primary purpose of the project is to increase specifying agency confidence in EFF by providing data on excavatability and the impact of component materials on EFF engineering properties.

**EFF Research Objectives**

The objectives of the proposed research are as follows:

1) Determine the long-term excavatability of flowable fill mixtures containing various quantities of Portland cement and ASTM C 618 Class F fly ash under field conditions and correlate the findings with compressive strength development in the laboratory.
2) Determine the long-term excavatability of flowable fill mixtures containing various quantities of Portland cement and high-unburned carbon fly ash under field conditions and correlate the findings with compressive strength development in the laboratory.
3) Determine if varying aggregate type significantly influences the results of objective 1.
4) Prepare a model specification for EFF in Kentucky and Tennessee based on the results of the project. Distribute the results of the project and the model specification on a CD-ROM to municipal officials and other users of flowable fill in Kentucky and Tennessee through the Kentucky and Tennessee Ready Mixed Concrete Associations.

**EFF Literature Review**

Table 1 shows some specifications / recommendations for compressive strength limitations for excavatability.

**Table 1. Compressive Strength Limitations (in psi) for EFF Excavatability**

| Organization | Compressive Strength Limits (psi) |
|---|---|
| ACI 229R-99 (1) | Manual < 50<br>Mechanical 100-200 |
| National Ready Mixed Concrete Assoc. (2) | 30-200 |
| Illinois DOT (3) | 150 @ 180 days |
| Georgia DOT (4) | 100 @ 28 days |
| Florida DOT (5) | 100 @ 28 days |
| Bhat and Lovell (6) | 80 - 150 by hand |
| Indiana Ready Mixed Concrete Assoc. (7) | 150 |
| Virginia Ready Mixed Concrete Assoc. (8) | 200 |

EFF mixtures need to have a very fluid consistency and yet not segregate too rapidly or extensively to perform adequately. The obvious solution to this problem is to increase the amount of paste components in the mixtures. However, increasing the Portland cement and fly ash contents also increase EFF compressive strength and thus reduce its excavatability. The effect of a Portland cement increase on EFF strength becomes rapidly obvious and most designers have recognized this fact. However, the effect of a fly ash increase, particularly a Class F fly ash increase, on EFF strength is not rapidly evident. Meade, Hunsucker, and Stone (9) reported that the two-year strength of EFF containing over 350 lbs/CY of Class F fly ash may be four to five times the 28-day strength. The slow strength development is due to a pozzolanic reaction between Portland cement hydration

products and the Class F fly ash. The long term effect of the pozzolanic reaction on compressive strength is apparently not well understood by some EFF designers.

The paste content of the mixture may also be increased using EFF air generators. EFF generators produce high contents of stable air bubbles in the mixture. The high content of stable air bubbles:

- Limits ultimate strength
- Improves workability
- Reduces segregation
- Reduces shrinkage and virtually eliminates bleeding
- Reduces unit weight

In 1996, Rogers Group Inc. sponsored a project to determine if aggregate production byproducts containing high dust contents were a viable EFF aggregate. It was determined that high-fines limestone screenings containing up to 21 percent passing the Number 200 Sieve could be used as aggregates for air-entrained EFF mixtures (10). Experience garnered from several EFF projects suggests that compressive strength development and excavation difficulty are a function of five factors:

1) Air content
2) Portland cement content
3) Supplementary cementitious materials character and content
4) Aggregate type and gradation
5) Water content

**EFF Performance Criteria**

Table 2 shows consensus performance criteria selected for this study.

**Table 2. EFF Performance Criteria**

| Criteria | Limit |
|---|---|
| Flow | ≥ 8-inch |
| Ball Drop | ≤ 24 hour |
| 28-day Compressive Strength | ≥ 30-psi |
| Ultimate Compressive strength | ≤ 150-psi |

**EFF Mixtures**

Table 3 shows nine EFF mixtures used to assess the impact of Class F Fly Ash and Portland cement content. Proportions for the EFF mixtures were chosen using Kentucky Transportation Cabinet (11) and Tennessee Ready Mixed Concrete Association (TRMCA) recommendations as well as a previous Tennessee Technological University (TTU) capping research mixture (12). Portland cement contents ranged from 30 to 60 lbs/CY. Class F fly ash contents ranged from 300 to 440 lbs/CY. The fine aggregate used was river sand.

Table 4 shows six EFF mixtures used to assess the impact of Portland cement content and high-unburned carbon fly ash content. Portland cement contents of 45 and 60 lbs/CY and high-unburned carbon fly ash contents of 370, 440, 510 lbs/CY were used to evaluate the impact of component proportions. The fine aggregate used was river sand.

The influence of aggregate type on EFF mixtures was evaluated by using five different aggregate types in the TRMCA EFF mixture as shown in Tables 5 and 6. Two additional aggregate variable mixtures were planned:

- Trench 20 oily foundry sand and
- Trench 21 clayey foundry sand

Oily foundry sand aggregate was not available at the time of trench placement. Clayey foundry sand contained such large metal fragments that local ready mix producers would not allow it in their mixers. Therefore, neither of the trenches was placed. Four additional comparison EFF mixtures (Table 7) were also used in the study.

**Table 3. EFF Mixtures with Type I PC, Class F Fly Ash, and River Sand**

| Mixture | Date Placed | PC (lbs/CY) | Fly Ash (lbs/CY) | Water (lbs/CY) | Aggregate (lbs/CY) | Flow (in) | Ball Drop (hrs) |
|---|---|---|---|---|---|---|---|
| 1 KTC | 3/12/01 | 30 | 300 | 550 | 3000 | 0 | 22 |
| 2 | 3/12/01 | 30 | 370 | 501 | 2560 | 0 | 21 |
| 3 | 3/12/01 | 30 | 440 | 491 | 2508 | 9.5 | 21 |
| 4 | 3/12/01 | 45 | 300 | 510 | 2603 | 10.5 | 20 |
| 5 TRMCA | 3/12/01 | 45 | 370 | 499 | 2552 | 11 | 19 |
| 6 | 5/14/01 | 45 | 440 | 490 | 2499 | 11 | 20 |
| 7 | 5/16/01 | 60 | 300 | 508 | 2595 | 0 | 19 |
| 8 | 5/16/01 | 60 | 370 | 500 | 2538 | 0 | 18 |
| 9 TTU CAP | 5/16/01 | 60 | 440 | 498 | 2497 | 18 | 19 |

**Table 4. EFF Mixtures with Type I PC, High Unburned Carbon Fly Ash, and River Sand**

| Mixture | Date Placed | PC (lbs/CY) | Fly Ash (lbs/CY) | Water (lbs/CY) | Aggregate (lbs/CY) | Flow (in) | Ball Drop (hrs) |
|---|---|---|---|---|---|---|---|
| 10 | 5/15/01 | 45 | 370 | 515 | 2697 | 0 | 19 |
| 11 | 5/15/01 | 60 | 370 | 509 | 2600 | 8.5 | 18 |
| 12 | 5/15/01 | 45 | 440 | 500 | 2557 | 14 | 71 |
| 13 | 5/15/01 | 60 | 440 | 494 | 2560 | 15.5 | 66 |
| 14 | 5/15/01 | 45 | 510 | 481 | 2527 | 15 | 69 |
| 15 | 5/15/01 | 60 | 510 | 479 | 2520 | 16 | 66 |

**Table 5. Aggregate Variables for TRMCA (45 PC / 370 F Ash) EFF Mixture**

| Mixture Number / Fine Aggregate | Date Placed | Water (lbs/CY) | Aggregate (lbs/CY) | Flow (in) | Ball Drop (hrs) |
|---|---|---|---|---|---|
| 5 River Sand | 3/12/01 | 499 | 2552 | 11 | 19 |
| 16 Limestone Manufactured Sand | 5/14/01 | 499 | 2552 | 11 | 48 |
| 17 Crushed Sandstone | 5/14/01 | 593 | 2362 | 0 | 22 |
| 18 Masonry Sand | 5/14/01 | 641 | 2190 | 12.5 | 44 |
| 19 Limestone Screenings | 5/14/01 | 448 | 2611 | 10.5 | 23 |
| 20 Oily Foundry Sand* | | | | | |
| 21 Clayey Foundry Sand* | | | | | |

* - Not placed

**Table 6. Variable Aggregate Specifications**

| Aggregate Type | Specification |
|---|---|
| Crushed sandstone | TDOT PCC Fine Agg. – near ASTM C 33 (13) |
| Manufactured Limestone Sand | TDOT PCC Fine Agg. – near ASTM C 33 (13) |
| Masonry Sand (high silica dredged sand) | Near ASTM C 144 |
| Limestone Screenings | AASHTO M43 Size Number 10 (14) |
| Oily Foundry Sand* | None |
| Clayey Foundry Sand* | None |

* - Not placed

**Table 7. EFF Comparison Mixtures**

| Mixture | Date Placed | PC (lbs/CY) | Fly Ash (lbs/CY) | Water (lbs/CY) | Agg. (lbs/CY) | Flow (in) | Air (%) | Ball Drop (hrs) |
|---|---|---|---|---|---|---|---|---|
| 22 TDOT (15) | 5/14/01 | 100 | 250 | 500 | 2800* | 0 | ---- | 21 |
| 23 MB AE 90 | 5/15/01 | 100 | 0 | 340 | 2439* | 8.75 | 28.3 | 46 |
| 24 WRG Darafill | 5/15/01 | 100 | 0 | 270 | 2316* | 6.25 | 24.3 | 20 |
| 25 MBT Rheofill | 5/15/01 | 80 | 0 | 375.3 | 2501** | 7.25 | 25.9 | 67 |

* - River Sand , ** - Limestone Manufactured Sand

**EFF Procedure**

Approximately 5.5 cubic yards of each EFF mixture was delivered to the TTU campus in a ready mix truck. 5.33 cubic yards of each mixture was placed in a 3-feet deep, 3-feet wide, 16-feet long trench simulating a utility cut. The remainder of the mixture was used to cast compressive strength cylinders and conduct plastic property tests.

Each mixture was sampled near the middle of the batch in accordance with ASTM D 5791 (16). The consistency of each mixture was determined as per ASTM D 6103 (17). The unit weight and air content of each mixture were determined in accordance with ASTM D 6023 (18). Flow values and air contents (for air-entrained mixtures only) are shown in Tables 3, 4, 5, and 7. Fifty 4-inch diameter, 8-inch height, compressive strength cylinders of each mixture were cast in accordance with ASTM D 4832-95 (19) with the following exceptions:

- Cardboard molds were used rather than plastic due to stripping difficulties with CLSM in plastic molds;
- CLSM was not mounded on top of the cylinder in the plastic state and removed after hardening with a wire brush due to the high potential for cylinder damage.

All EFF compressive strength cylinders were initially cured in the molds with the tops covered with plastic bags secured by rubber bands. The cylinders were stored in wooden cabinets that were exposed to typical laboratory conditions (temperature and humidity). Unpublished preliminary research with some of the same EFF mixture designs had shown that the cylinders disintegrated when submerged in water. When testing the cylinders at 546 days of age, many of the specimens had become extremely

dry and brittle. It was determined that sufficient samples remained to submerge one-half of them in a lime-water curing tank for the duration of the project to determine the effect submerged curing at a late age would have on compressive strength. Compressive strength tests at 637 and 728 days used both samples that were cured in the molds and samples that were immersed at 546 days age. Complete compressive strength data can be found in Appendix A. In the body of the report on the larger of the two average compressive strengths was reported and used for correlations.

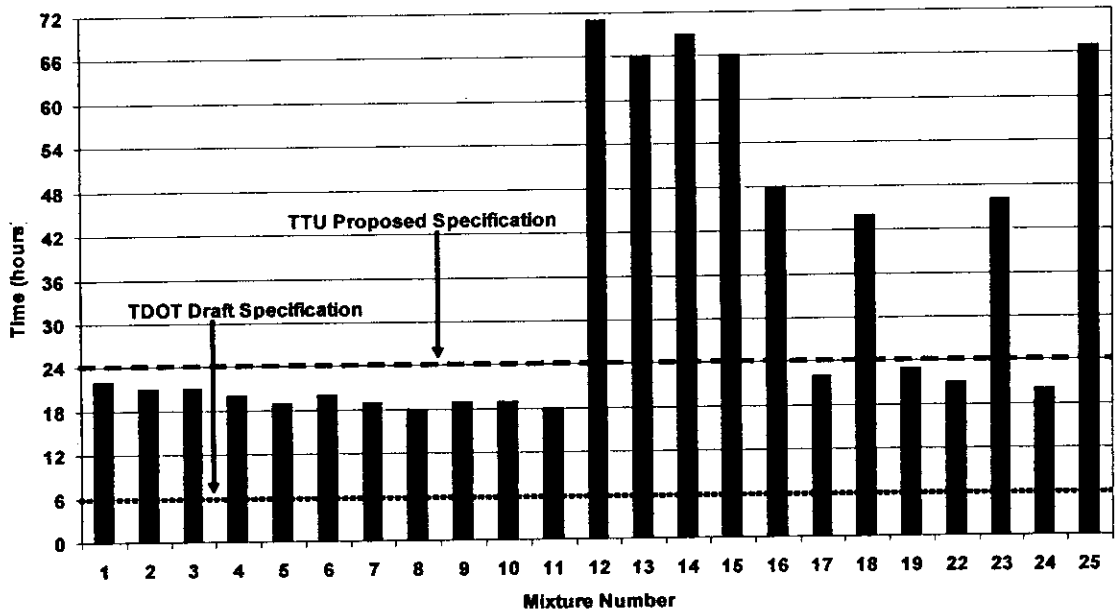
Three compressive strength cylinders were tested at each time shown in Table 8, providing that sufficient cylinders survived transportation and mold stripping. The compressive strength testing was conducted in accordance with ASTM D 4832-95 with the following exception. Compressive strength cylinders were capped with wet-suit neoprene in rigid retaining caps as described by Sauter and Crouch (12).

**Table 8. Testing Times**

| **Days** | 7 | 28 | 63 | 98 | 140 | 182 | 238 | 301 | 364 | 455 | 546 | 637 | 728 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Weeks** | 1 | 4 | 9 | 14 | 20 | 26 | 34 | 43 | 52 | 65 | 78 | 91 | 104 |
| **Years** | | | | | | 0.5 | | | 1 | 1.25 | 1.5 | 1.75 | 2 |

The EFF trenches were tested for suitability for load application at approximately 6 hours after placement and subsequently every 2 to 4 hours during regular work hours until each mixture passed the test or 7 days elapsed. The test was conducted as prescribed in ASTM D 6024 (20). The time each trench passed ASTM 6024 is shown in Tables 3, 4, 5, and 7 and Figure 1.

**Figure 1. Comparison of Times to Pass ASTM Ball Drop Test**




Two Dynamic Cone Penetrometer (DCP) tests (21) were conducted on each trench on Monday 3/10/03. Several attempts were made to push Shelby Tubes and obtain compressive strength samples; however, no viable samples were recovered. Two attempts to excavate the EFF in each trench with a Case 580E backhoe were made on Tuesday 3/11/03. The backhoe operator provided a 1 to 10 (10 hardest) estimate of excavation difficulty for each trench. In addition, two attempts to excavate each trench were made with a sharpshooter shovel. Further, two pick penetration tests were conducted on each trench. Trenches containing mixtures 1 through 5 were two years old at the time of testing and excavation, the remainder of the trenches were approximately 22 months old.

**EFF Results**

The average values of 28-day, maximum obtained, and compressive strengths at excavation (637 or 728-day) are shown in Table 9. Complete compressive strength results are available in Appendix A. Results of EFF trench testing just prior to excavation and excavation difficulties are shown in Table 10. The operator deemed all EFF mixtures excavatable. However, excavation difficulty varied considerably.

**Table 9. 28-day, Maximum, and Excavation Compressive Strengths**

| Mixture | Aggregate | 28-day Compressive Strength (psi) | Maximum Compressive Strength (psi) | Excavation (637 or 728) Compressive Strength (psi) |
|---|---|---|---|---|
| 1 KTC 30/300 F | River Sand | 6 | 10 | 7 |
| Mixture 2 30/370 F | River Sand | 10 | 15 | 12 |
| Mixture 3 30/440 F | River Sand | 13 | 22 | 17 |
| Mixture 4 45/300 F | River Sand | 20 | 48 | 48 |
| 5 TRMCA 45/370 F | River Sand | 17 | 41 | 29 |
| Mixture 6 45/440 F | River Sand | 20 | 68 | 68 |
| Mixture 7 60/300 F | River Sand | 17 | 99 | 48 |
| Mixture 8 60/370 F | River Sand | 27 | 90 | 66 |
| 9 TTU Cap 60/440 F | River Sand | 40 | 145 | 128 |
| 10 45/370 HC | River Sand | 34 | 94 | 84 |
| 11 60/370 HC | River Sand | 41 | 144 | 101 |
| 12 45/440 HC | River Sand | 20 | 30 | 26 |
| 13 60/440 HC | River Sand | 31 | 83 | 64 |
| 14 45/510 HC | River Sand | 29 | 68 | 58 |
| 15 60/510 HC | River Sand | 29 | 137 | 132 |
| 16 45/370 F | LS Man. Sand | 49 | 106 | 76 |
| 17 45/370 F | Crushed Sandstone | 24 | 126 | 94 |
| 18 45/370 F | Masonry Sand | 48 | 128 | 104 |
| 19 45/370 F | LS Screenings | 58 | 134 | 119 |
| 22 TDOT 100/250 | River Sand | 40 | 201 | 159 |
| 23 MBT MB AE 90 | River Sand | 16 | 39 | 29 |
| 24 W. R. Grace Darafill | River Sand | 36 | 78 | 55 |
| 25 MBT Rheofill | LS Man. Sand | 17 | 46 | 41 |

## Table 10. Trench Testing and Excavation Results

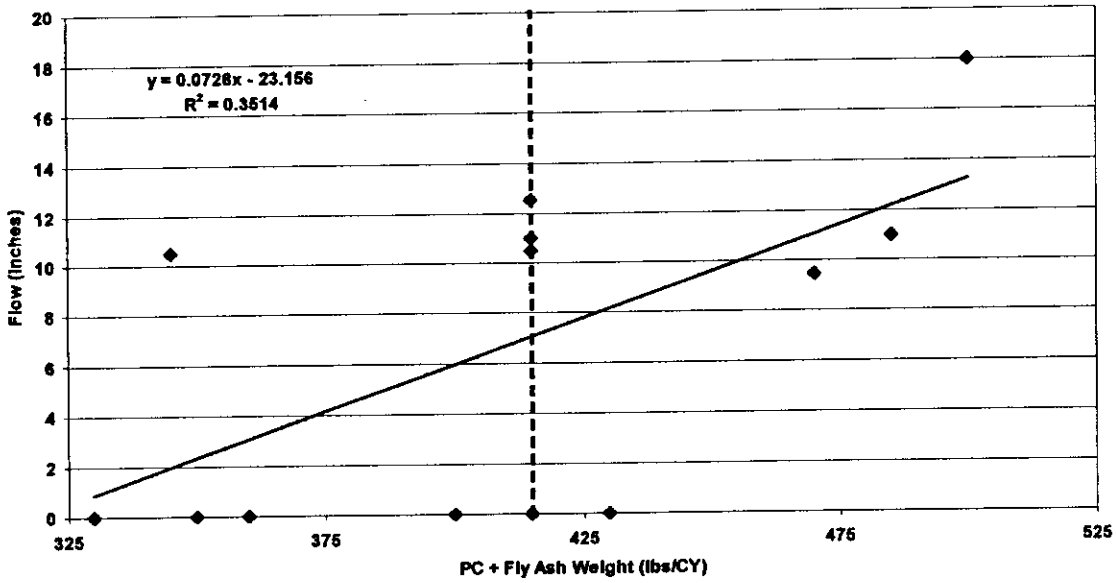
| Mixture | Average Comp. Strength @ Excavation (psi) | Average Dynamic Cone Penetrometer (psf) | Case 580E Backhoe | | Manual Excavation | |
|---|---|---|---|---|---|---|
| | | | Average Hydraulic Line Pressure (psi) | Average Operator Rating (1-10) | Average Shovel Difficulty (1-10) | Average Pick Penetration (inches) |
| 1 KTC 30/300 | 7 | 5000 | 1450 | 1 | 1 | 1.85 |
| Mixture 2 30/370 | 12 | >10,000 | 1668 | 3 | 10 | 1.65 |
| Mixture 3 30/440 | 17 | >10,000 | 1740 | 4 | 10 | 2.1 |
| Mixture 4 45/300 | 48 | >10,000 | 1813 | 7 | 9 | 1.35 |
| 5 TRMCA 45/370 | 29 | 7500 | 1269 | 7 | 10 | 1.65 |
| Mixture 6 45/440 | 68 | >10,000 | 1849 | 8 | 9 | 1.65 |
| Mixture 7 60/300 | 48 | >10,000 | 1958 | 7 | 10 | 1.45 |
| Mixture 8 60/370 | 66 | 9000 | 1523 | 8 | 9 | 1.95 |
| 9 TTU Cap 60/440 | 128 | >10,000 | 1450 | 9 | 9 | 2.5 |
| 10 45/370 HC | 84 | 7500 | 1595 | 7 | 8 | 3.35 |
| 11 60/370 HC | 101 | >10,000 | 1523 | 9 | 9 | 1.65 |
| 12 45/440 HC | 26 | 3250 | 1595 | 4 | 1 | 5.1 |
| 13 60/440 HC | 64 | 3500 | 2175 | 3 | 3 | 3.95 |
| 14 45/510 HC | 58 | 3250 | 2175 | 3 | 2 | 4.65 |
| 15 60/510 HC | 132 | >10,000 | 2030 | 6 | 9 | 2.95 |
| 16 LS Man. Sand 45/370 | 76 | 4500 | 2030 | 9 | 9 | 3.95 |
| 17 Crushed SS 45/370 | 94 | >10,000 | 1740 | 8 | 9 | 1.9 |
| 18 Masonry Sand 45/370 | 104 | 8000 | 2248 | 7 | 7 | 2.55 |
| 19 LS Scr. 45/370 | 119 | 6500 | 1813 | 9 | 10 | 2.7 |
| 22 TDOT 100/250 | 159 | >10,000 | 1595 | 10 | 10 | 0.65 |
| 23 MBT MB AE 90 | 29 | 2750 | 2103 | 3 | 1 | 5.15 |
| 24 W. R. Grace Darafill | 55 | 5750 | 2030 | 6 | 9 | 3.1 |
| 25 MBT Rheofill LS Man. Sand | 41 | 2000 | 1885 | 4 | 1 | 6.5 |

**Analysis of EFF Results**

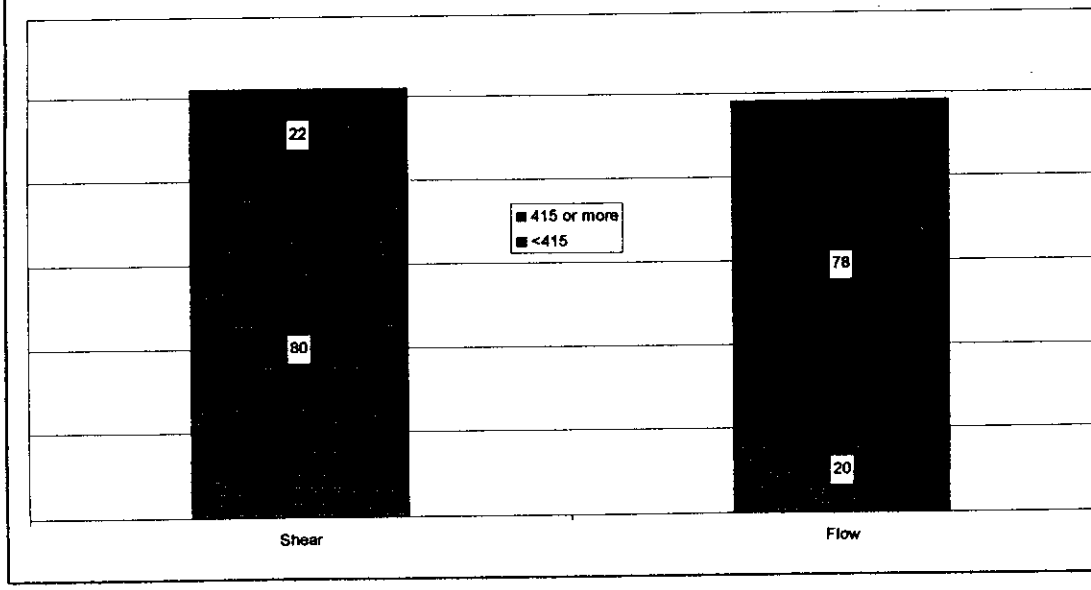
Mixtures 9 (TTU Cap 60/440 river sand), 11 (60 / 370 high carbon ash, river sand), and 19 (TRMCA 45/370 limestone screenings) were the only three mixtures complying with all the criteria shown in Table 2. However, the use of high carbon ash typically extended the time required to pass the ball drop test. Mixtures 6 and 12 only differed in ash type, but mixture 12 took over three times as long to pass ball drop. Similarly, mixtures 9 and 13 only differed in ash type, but mixture 13 took over three times as long to pass ball drop. High carbon ash mixtures also generated some erratic strength results. Mixtures 12 and 13 should have been stronger than mixture 11 due to higher cementitious contents; however both were weaker than mixture 11. Therefore, the research team was hesitant to recommend the use of mixtures containing high carbon ash without further research.

Figure 2 shows a correlation between ASTM D 6103 flow and cementitious materials content of the PC-ash mixtures. Although the coefficient of determination is low (0.3514), it is interesting to note that for EFF mixtures with a cementitious materials content of 415 lbs/CY or more, 78 percent had a flow greater than 8 inches. However, for EFF mixtures with cementitious materials content less than 415 lbs/CY, only 20 percent had a flow greater than 8 inches. Figure 3 shows a graphical illustration of importance of cementitious materials content to EFF flow.

## Figure 2. Flow vs. Cementious Materials Content for PC-F Ash Mixtures




## Figure 3. Passing the Flow Test: Is 415 lbs/CY of PC + Class F Fly Ash the Magic Number for Non-AE EFF Mixtures?



Time to pass the ASTM D 6024 Ball Drop Test for the PC-ash mixtures did not correlate well with mixture composition. However, 87.5 percent of non-air-entrained PC-F Ash EFF mixtures with cementitious materials contents less than or equal to 500 lbs/CY passed the ASTM D 6024 ball drop test in less than 24 hours. It was likely that high (> 500 lbs/CY) cementitious materials content inhibited bleeding of the EFF mixtures, thus retarding dewatering and subsequent stiffening. No correlation to time to pass the ball drop test was attempted with the limited number of air-entrained EFF mixtures.

Figure 4 shows a correlation between 28-day compressive strength and PC weight cubed times fly ash weight for Class F fly ash in River sand mixtures. The $R^2$ of 0.8198 indicates a fairly strong relationship. Figure 5 shows maximum compressive strength versus PC weight squared times fly ash content for Class F fly ash in River sand mixtures. The excellent fit ($R^2 = 0.9687$) of the linear trend line shows mathematically what the industry personnel have intuitively known for some time – EFF potential compressive strength is directly proportional to cementitious materials content. PC content of the PC-Class F fly ash EFF mixtures is more influential for early compressive strength development (28-day) than for maximum compressive strength as indicated by the cubed and squared PC weight relationships. Similar correlations for PC-High Unburned Carbon Ash were very poor, indicating no relationships.

**Figure 4. Comparison of 28-day Compressive Strength and Cementitious Materials Content for Class F Fly Ash, River Sand Mixtures**

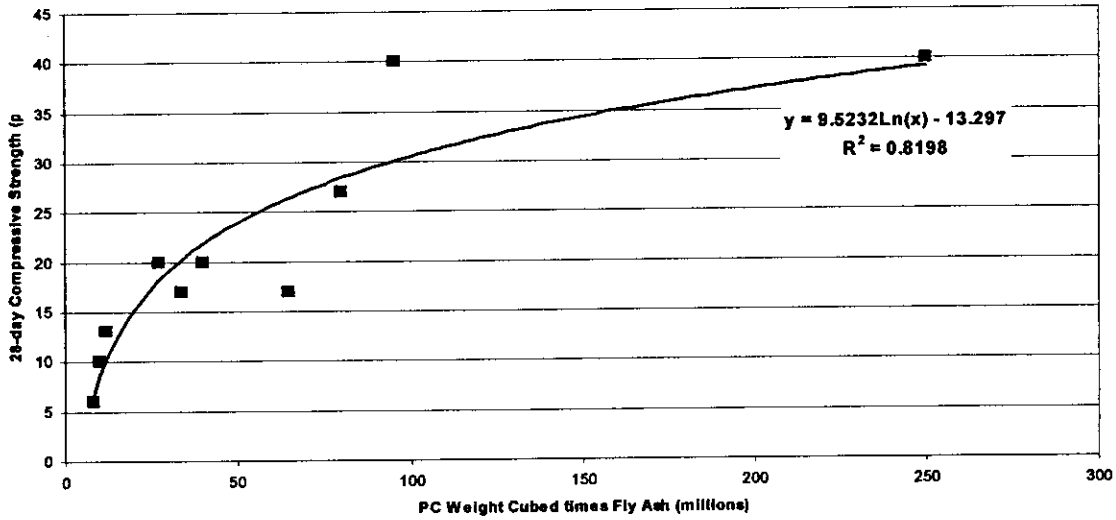
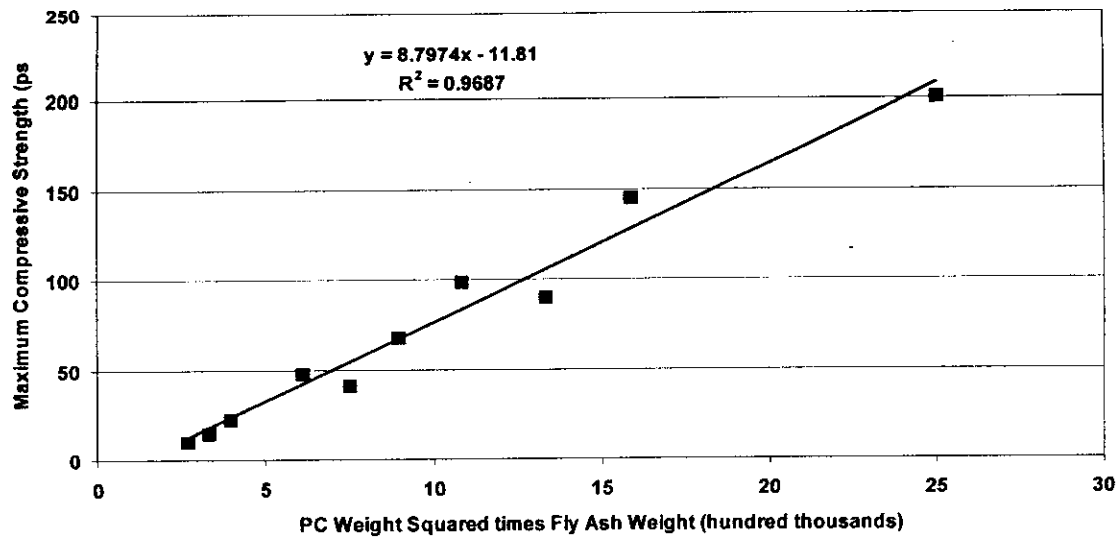


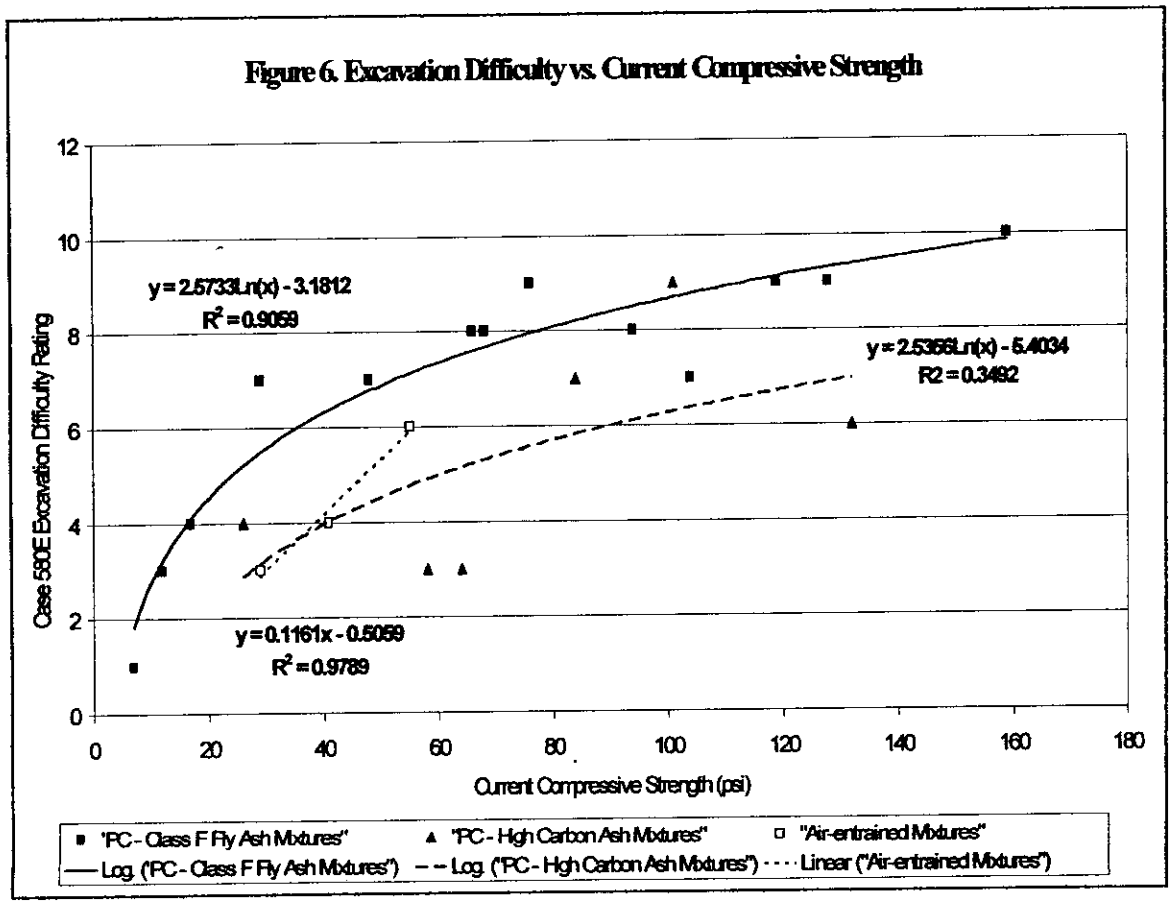

**Figure 5. Comparison of Maximum Compressive Strength and Cementitious Materials Content for Class F Fly Ash, River Sand Mixtures**



Substitution of variable aggregates for river sand into the TRMCA EFF mixture yielded few useful observations. Flow of all the mixtures was similar except for the crushed sandstone mixture. The locally available crushed sandstone often has more than 55 percent of the particles by weight between the No. 30 and No. 50 sieves, leading to a very open gradation prone to bleeding and segregation. No viable explanation could be developed for the difference in time to pass the ball drop. River sand reduced both 28-day and maximum compressive strengths. Limestone screenings produced the highest 28-day and maximum compressive strengths. Although Case 580E operator ratings for excavation difficulty for all the aggregate variable mixtures were similar, compressive strengths and other trench testing results varied widely. The importance of cementitious materials content to flow, time to pass the ball drop, and compressive strength development shown in Figures 2 through 5 suggest that the cementitious materials content of a PC-Class F fly ash EFF mixture is extremely important to mixture performance. Unfortunately, it appears that compressive strength cementitious materials relationships are aggregate dependent.

Figure 6 shows correlations between current compressive strengths at the time of excavation and Case 580E backhoe excavation difficulty. Good relationships were obtained for PC-Class F fly ash mixtures with all aggregate types included and for air-entrained mixtures. Only three air-entrained mixtures were available for correlation. Air-entrained mixtures are easier to excavate than non-air-entrained mixtures at the same compressive strength. A poor correlation was obtained with PC-high unburned carbon ash mixtures indicating no relationship. DCP, Case 580E hydraulic line pressure,

sharpshooter shovel, and pick penetration data did not correlate well will with mixture composition or excavation difficulty rating.




Mr. William Brewer, P.E., former chair of ACI Committee 229 on CLSM, developed a "Removability Modulus" for Hamilton County and the City of Cincinnati, Ohio. Brewer (22) showed that the excavatability of an EFF mixture is a function of compressive strength and unit weight. The findings of this project support that conclusion. The Excavatability Index (EI) is a modification of an equation developed by Mr. Brewer to fit the data obtained in this study. The modified equation shown below was developed such

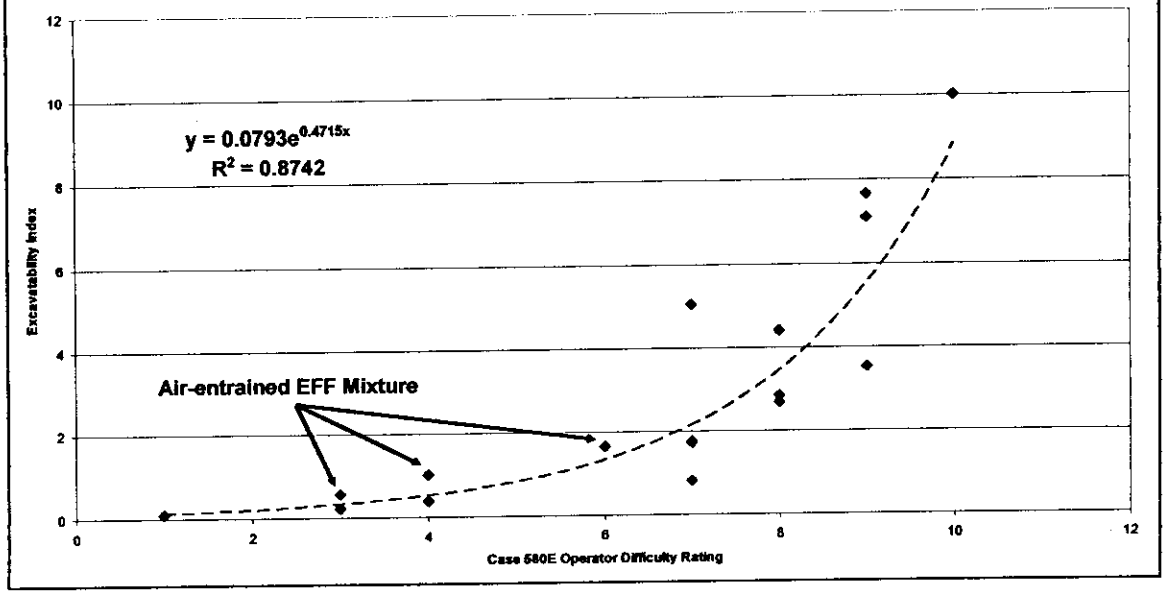
that values less than 10.0 indicate that the EFF mixture is excavatable with a Case 580E backhoe.

$EI = [(\text{Comp. strength @ excavation in psi})^{1.5} \times (\text{plastic unit weight in pcf})^{1.285})]/100000$

**Table 9. Excavation Indices for EFF without High Carbon Ash**

| Mixture | Average Compressive Strength @ Excavation (psi) | Plastic Unit Weight (pcf) | Excavation Index |
|---|---|---|---|
| 1 KTC 30/300 | 7 | 131.8 | 0.10 |
| Mixture 2 30/370 | 12 | 135 | 0.23 |
| Mixture 3 30/440 | 17 | 132.3 | 0.37 |
| Mixture 4 45/300 | 48 | 131.6 | 1.76 |
| 5 TRMCA 45/370 | 29 | 131 | 0.82 |
| Mixture 6 45/440 | 68 | 121.8 | 2.68 |
| Mixture 7 60/300 | 48 | 130 | 1.73 |
| Mixture 8 60/370 | 66 | 131.8 | 2.84 |
| 9 TTU Cap 60/440 | 128 | 131.6 | 7.66 |
| 16 LS Manufactured Sand 45/370 | 76 | 132.4 | 3.53 |
| 17 Crushed Sandstone 45/370 | 94 | 122.4 | 4.39 |
| 18 Masonry Sand 45/370 | 104 | 121 | 5.03 |
| 19 LS Screenings 45/370 | 119 | 135.2 | 7.11 |
| 22 TDOT 100/250 | 159 | 126 | 10.02 |
| 23 MBT MB AE 90 | 29 | 98.6 | 0.57 |
| 24 W. R. Grace Darafill | 55 | 106.7 | 1.65 |
| 25 MBT Rheofill LS Manufactured Sand | 41 | 103.8 | 1.02 |

**Figure 7. Excavatability Index vs. Operator Rating for All Mixtures without High Carbon Ash**




## EFF Conclusions

The following conclusions can be drawn from the limited data available:

1) Non-air-entrained PC-F Ash EFF mixtures with cementitious materials contents of 415 lbs/CY or greater have a much higher probability (78%) of achieving an ASTM D 6103 flow greater than 8 inches than similar EFF mixtures with lower cementitious materials contents (probability = 22%).
2) 85.7 percent of non-air-entrained PC-F Ash EFF mixtures with cementitious materials contents less than or equal to 500 lbs/CY passed the ASTM D 6024 ball drop test in less than 24 hours.
3) There appears to be a good relationship between 28-day compressive strength and PC weight cubed times fly ash weight for non-air-

entrained PC-Class F fly ash EFF mixtures. Unfortunately, the relationship appears to be aggregate dependent.

4) There appears to be an excellent relationship between maximum (potential) compressive strength and PC weight squared times fly ash weight for non-air-entrained PC-Class F fly ash EFF mixtures. Unfortunately, the relationship appears to be aggregate dependent.
5) Uniform crushed sandstone fine aggregates with 55 percent or more of the particles by weight between the No. 30 and No. 50 sieves are likely to produce EFF mixtures that bleed excessively and are prone to segregation and flow problems.
6) Limestone screenings produced the highest 28-day and maximum compressive strengths in PC-F Ash EFF mixtures. River sand produced the lowest 28-day and maximum compressive strengths in PC-F Ash EFF mixtures.
7) The PC content of non-air-entrained PC-Class F fly ash EFF mixtures appears to be more important to early compressive strength development.
8) There appears to be a strong relationship between compressive strength of non-air-entrained PC-Class F fly ash EFF mixtures and excavation difficulty.

9) The use of high carbon ash typically extended the time required to pass the ball drop test and generated some erratic strength results. Therefore, the research team was hesitant to recommend the use of mixtures containing high carbon ash without further research.

10) There appears to be an excellent relationship between compressive strength of air-entrained EFF mixtures and excavation difficulty. Further, air-entrained EFF mixtures are easier to excavate at the same compressive strength than non-air-entrained PC-Class F fly ash EFF mixtures.

11) The Excavation Index (EI) combines the effects of compressive strength and density to predict excavatability. EFF mixtures with EI < 10.0 are excavatable with a Case 580E backhoe.

**EFF Recommendations**

1) The two mixtures shown in Table 10 are field-proven to comply with the criteria shown in Table 11.

**Table 10. Field Proven EFF Mixtures**

| Mixture | Portland Cement | Class F Fly Ash | Aggregate | Water |
|---|---|---|---|---|
| TTU Cap River Sand | 60 | 440 | 2492 | 498 |
| Limestone Screenings | 45 | 370 | 2611 | 448 |

**Table 11. Final Criteria and Results of Field Proven EFF Mixtures**

| Criteria | Limit | TTU Cap River Sand | Limestone Screenings |
|---|---|---|---|
| Flow | ≥ 8-inch | 18 | 10.5 |
| Ball Drop | ≤ 24 hours | 19 | 23 |
| 28-day Compressive Strength | ≥ 30-psi | 40 | 58 |
| Excavatability with Case 580E backhoe | ≤ 159-psi | 128 | 119 |
| Excavatability Index | ≤ 10.0 | 7.66 | 7.11 |

2) For non-air-entrained PC-F Ash EFF mixtures use 415-500 lbs/CY of PC plus Class F fly ash.

**EFF Technology Transfer**

Technology transfer was accomplished by preparing a minimum of 1000 copies of a CD-ROM containing the project results and a model specification for EFF. The CD-ROMs were distributed by holding four seminars (Nashville 7/16/03 and Knoxville 7/17/03 in Tennessee, and Frankfort 8/13/03 and Owensboro 8/14/03 in Kentucky) for ready mix producers, municipal and state specifying officials. The CD-ROMs were also to be distributed by TRMCA and KRMCA. The CD-ROMs and associated seminars were funded by KRMCA. Additional technology transfer was given through a presentation at the ASTM Symposium on Innovations in Controlled Low-Strength Material (Flowable Fill) on June 19, 2003 in Denver, Colorado. A paper entitled "Long Term Study of 23 Excavatable Tennessee CLSM Mixtures" was submitted for possible publication in ASTM STP 1459 (at the discretion of the ASTM Committee on Publications).

**EFF Acknowledgements**

The authors would like to express their appreciation to the Tennessee Department of Transportation, the Combustion Byproducts Recycling Consortium, Tennessee Ready Mixed Concrete Association, and Kentucky Ready Mixed Concrete Association for their financial support of the project. The authors express their appreciation to the Builders Supply Do-It Center, Irving Materials Inc., Plateau Ready Mix, SEFA, Rogers Group Inc., Master Builders Technologies, and W. R. Grace Construction Products for their donations of materials to the project. Special thanks to Woody Crawley, Larry Clouse, Jeremy Bloomburg, Rod Gamble, Dale Cathey, Jay Coleman, Joe Fitts, and Landon Deel. The authors would like to thank all TDOT employees, especially Steve M. Hall, Brian Egan, Heather Hall, Danny Lane and the members of the Coring Crew. The authors greatly appreciate the help in excavation of Joe Williams and Mark Neely, both of Tennessee Technological University. Special thanks to the following students who performed various tasks associated with the project: Rob Bailey, Shane Beasley, Audrey Copeland, Heather Sauter, Mark Cates, Kim Couch, Jesse Davis, Ted Dyer, Michael Ding, Michael Driver, Keith Honeycutt, Missy Jaynes, Adam Ledsinger, Vern Prentice, Ashley Price, Bart Romano, Danny Stooksbury, Sayward Touton, Adam Walker and Jamie Waller.

## EFF DISCLAIMERS

"This paper was prepared with the support of the US Department of Energy, Federal Energy Technology Center through its Cooperative Agreement No. DE-FC26-998FT40028 with West Virginia University Research Corporation. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of WVU or DOE."

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## ZOOM! CLSM

### ZOOM! Introduction

The Tennessee Department of Transportation Division of Materials & Tests saw a need for a rapid set, non-excavatable Controlled Low-strength Material (CLSM) for applications where time was a critical factor such as rapid subgrade repairs. CLSM initial set can occur in two ways: dewatering and chemical reactions. The research team decided that the CLSM should initially harden due to chemical reactions rather than by bleeding (dewatering) in case of unfavorable placement conditions. The new CLSM needed to set and gain compressive strength rapidly yet have a very fluid consistency while plastic. The new CLSM mixture was named ZOOM! to reflect the rapid set and strength gain.

### ZOOM! Research Objectives

Tennessee Technological University (TTU) researchers established the criteria shown in Table 12 for the ZOOM! mixture.

### ZOOM! Materials

Type I Portland Cement meeting ASTM C 150 (23) was selected. Local tap water was also used for all laboratory mixtures. An air-entraining admixture, conforming to ASTM C 260-97 (24), was used in all laboratory ZOOM batches. A commercially available powder-form CLSM air generator was used for ZOOM! field batches. The commercially available high-range water reducer and the water–reducing accelerator conformed to ASTM C 494 (25) Types F and E, respectively.

Commercially available, single-use cardboard molds (4 by 8-inch), reported by the manufacturer to be in compliance with ASTM C 470 (26), were used for all compressive strength samples. Commercially available wet-suit neoprene pads in ASTM C 1231 (27) rigid retainers were used for capping all compressive strength specimens.

**ZOOM! Proportions with Ohio River Sand (Control Fine Aggregate)**

The initial ZOOM! mixture was proportioned by trial batches in the laboratory at TTU with Ohio River Sand fine aggregate. The Ohio River Sand used is the common fine aggregate for Portland cement concrete in West and Middle Tennessee. The initial ZOOM! mixture proportions are shown in Table 13 and the initial plastic properties are shown in Table 14. Compressive strength cylinders of each mixture were cast in accordance with ASTM D 4832-95 (19) with the following exceptions:

- Cardboard molds were used rather than plastic due to stripping difficulties with CLSM in plastic molds;
- CLSM were not mounded on top of the cylinder in the plastic state and removed after hardening with a wire brush due to the high potential for cylinder damage.

Three compressive strength cylinders were tested at each time providing that sufficient cylinders survived transportation and mold stripping. The compressive strength testing was conducted in accordance with ASTM D 4832-95 with the following exception. Compressive strength cylinders were capped with wet-suit neoprene in rigid retaining caps as described by Sauter and Crouch (12).

ASTM D 6024 testing required a large quantity of CLSM. Since the large quantity required would have been difficult to produce in the laboratory, the research team decided to correlate ball drop results from EFF mixtures 1, 3, 5, 7, 9 with their average compressive strengths at the time each mixture passed the ball drop test. One-half cubic-foot batches were mixed and three cylinders made for each of the five EFF mixture designs. The cylinders were tested for compressive strength at the time each EFF mixture passed the ball drop test. It was thus determined that to pass the test for load application, ZOOM! CLSM needed to have a compressive strength greater than 6-psi at six hours.

**Other Fine Aggregates for ZOOM!**

Three additional fine aggregates were selected to represent the fine aggregate types commonly available across the state of Tennessee. Manufactured Limestone Sand is commonly used in East Tennessee. In addition, some concrete producers in the Cumberland Plateau Region use crushed sandstone fine aggregate. Limestone screenings were included due to their abundance in Middle and East Tennessee. The use of screenings would help address an industry-wide problem as well as reduce ZOOM! cost if the screenings proved to be a viable aggregate. Fine aggregate gradations, determined as per AASHTO T 11-96 (28) and AASHTO T 27-99 (29) are shown in Figure 8. Uncompacted void values, determined in accordance with AASHTO T 304-96 (30), are shown in Figure 9. Fine aggregate specific gravities and absorptions, determined in accordance with AASHTO T84-00 (31), are shown in Table 15.

**Table 12. ZOOM! CLSM Mixture Criteria**

| Parameter | Requirement |
|---|---|
| Application | Rapid-set structural fill or working platform |
| ASTM D 6024 Ball Drop Test (20) | Pass in 6 hours or less regardless of subgrade moisture |
| Bleeding | Little or no bleeding |
| Shrinkage | Little or no shrinkage |
| ASTM D 6103 Flow (17) | 8.75-inches minimum |
| ASTM D 6023 Air Content (18) | Prefer 20 to 30 percent |
| ASTM D 4832 compressive strength (19)* | 30-psi minimum at 24-hours |
| Excavatability | No requirement |
| Aggregates | Producible with a wide variety of Tennessee aggregates |

* -revised as recommended by Sauter and Crouch (12)

**Table 13. Initial ZOOM! CLSM Plastic Properties with Ohio River Sand Control Aggregate**

| Property | Ohio River Sand (Control Aggregate) | Requirement |
|---|---|---|
| Flow (inches) | 8.5 | 8.75 minimum |
| Bleed Time (min) | 4.5 | Little or no bleeding |
| Shrinkage | Minimal | Little or no shrinkage |
| Air Content (%) | 25.7 | 20 to 30 preferred |
| Unit Weight (pcf) | 104.6 | No requirement |
| Meet Requirements / Problems | No<br>Best combination of flow and bleeding achievable | |

**Table 14. Initial ZOOM! CLSM Mixture Proportions Developed from Trial Batches with Ohio River Sand Control Aggregate**

| Component | Amount |
|---|---|
| Type 1 Portland cement | 300 lbs/CY |
| Water | 317 lbs/CY |
| Ohio River Sand (SSD) | 2425 lbs/CY |
| Air-entraining agent | 70 oz/CY |
| High-range water reducer | 30 oz/CY |
| Accelerator | 225 oz/CY |

**Table 15. CLSM Aggregate Specific Gravities and Absorptions**

| Aggregate | Apparent SG | Bulk SG (dry) | Bulk SG (SSD) | Absorption (%) |
|---|---|---|---|---|
| Ohio River Sand (Control) | 2.645 | 2.583 | 2.607 | 0.93 |
| Manufactured Limestone Sand | 2.676 | 2.588 | 2.621 | 1.27 |
| Limestone Screenings | 2.760 | 2.676 | 2.708 | 1.11 |
| Crushed Sandstone | 2.658 | 2.611 | 2.628 | 0.65 |

**Figure 8. CLSM Fine Aggregate Gradation Comparison**

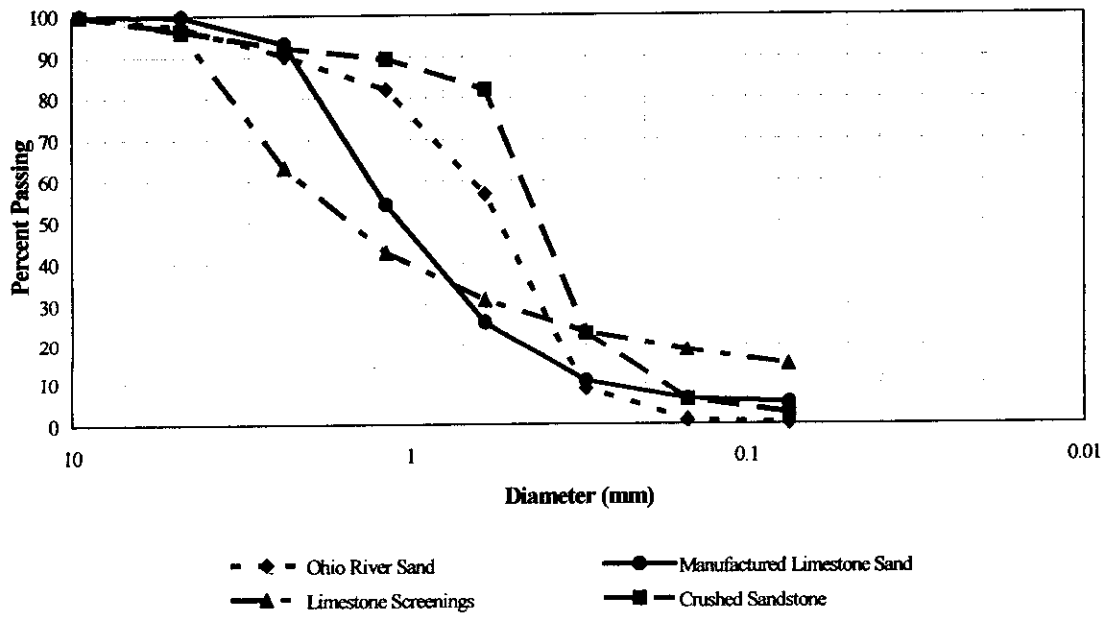
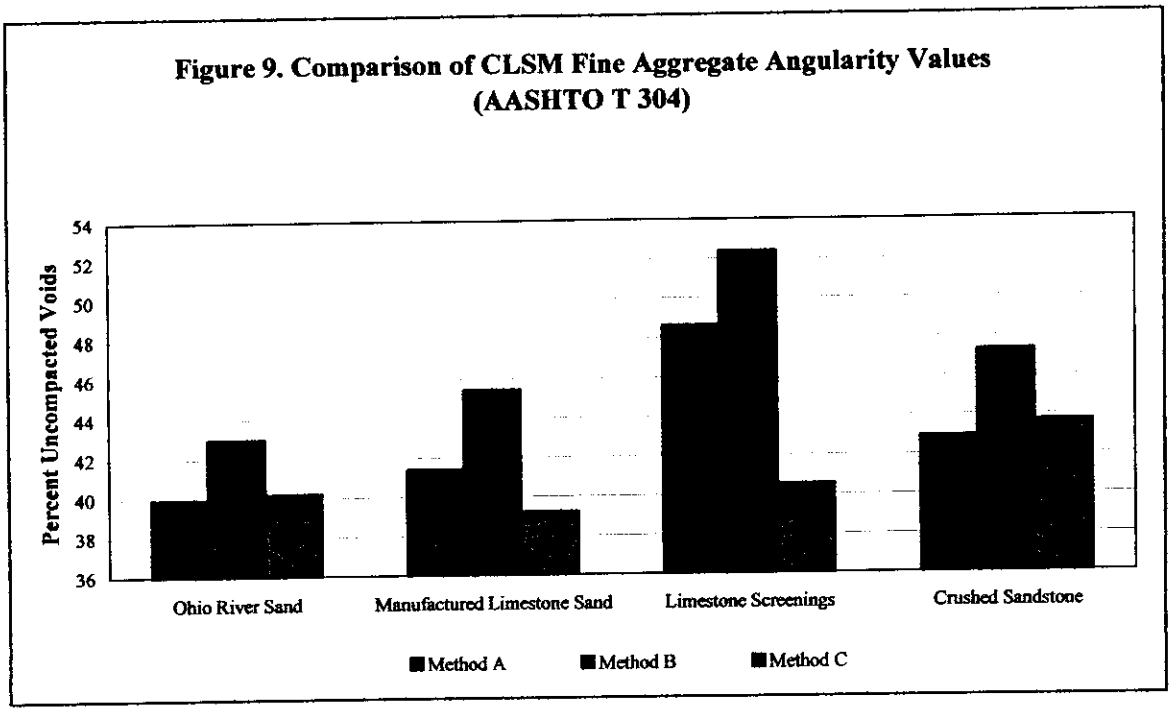


**Figure 9. Comparison of CLSM Fine Aggregate Angularity Values (AASHTO T 304)**




## Effects of Substitution of Other Fine Aggregates in ZOOM!

Table 16 shows a comparison of the critical fine aggregate properties for ZOOM! CLSM. Table 17 shows the plastic properties of the ZOOM! CLSM mixtures with other fine aggregates substituted for the Ohio River sand control aggregate. The properties of the other fine aggregates selected are compared with properties of the control aggregate. The following paragraphs describe the effects of the properties of other fine aggregates on properties of ZOOM! CLSM.

**Table 16. ZOOM! CLSM Aggregate Property Summary**

| Aggregate | % Passing #200 | FM | $C_u$ | T 304 $U_s$ | T 304 $U_m$ | T 304 $U_r$ |
|---|---|---|---|---|---|---|
| Ohio River Sand (Control) | 0.4 | 2.64 | 2.10 | 39.92 | 42.97 | 40.19 |
| Manufactured Limestone Sand | 5.1 | 3.10 | 5.93 | 41.41 | 45.43 | 39.22 |
| Limestone Screenings | 15.0 | 3.25 | 29.33 | 48.61 | 52.38 | 40.52 |
| Crushed Sandstone | 2.6 | 2.11 | 2.56 | 42.90 | 47.27 | 43.67 |

**Table 17. ZOOM! CLSM Plastic Properties for other Aggregates using the Control Aggregate Mixture Proportions**

| Property | Manufactured Limestone Sand | Limestone Screenings | Crushed Sandstone |
|---|---|---|---|
| Flow (inches) | 9.75 | Shear (No Flow) | 6.5 |
| Bleed Time (min) | No Bleeding | No Bleeding | No Bleeding |
| Shrinkage | No Shrinkage | No Shrinkage | No Shrinkage |
| Air Content (%) | 31.1 | 16.6 | 30.4 |
| Unit Weight (pcf) | 102.1 | 121.76 | 99.2 |
| Problems | None | Flow & Air | Flow |
| Possible Solutions | None Required | Increase air volume & paste fluidity | Make paste more fluid |

**A. Manufactured Limestone Sand**

Previous research at TTU (10) indicated that a more angular aggregate (as indicated by AASHTO T 304-96 Method B $U_m$ = 45.43) might entrain more air than the control aggregate ($U_m$ = 42.97). Air content increased from 25.7 percent for the control aggregate to 31.1 percent for manufactured limestone sand aggregate ZOOM!. Flow increased from 8.5 inches to 9.75 inches due to the increased air content. Bleeding was reduced by a denser gradation and higher fines content ($C_u$ = 5.93, 5.1%) compared to the control aggregate ($C_u$ = 2.10, 0.4%).

**B. Limestone Screenings**

Two conflicting factors effected air content of the ZOOM! limestone screenings mixture. As previously stated, more angular aggregates increase air entrainment. Limestone screenings are much more angular than the control aggregate as indicated by both AASHTO T 304 Methods A and B ($U_s$ = 48.61 and $U_m$ = 52.38 for limestone screenings vs. $U_s$ = 39.92 and $U_m$ = 42.97 for the control aggregate). However, the dominant factor was fines content (15% vs. 0.4%) reducing the air content from 25.7 percent to 16.6 percent.

Several factors reduced the flow of the limestone screenings ZOOM! mixture to zero. First, the particle shape ($U_s$ = 48.61 and $U_m$ = 52.38) of the limestone screenings approached a flat and elongate condition. ACI 221-96 (27) sited the work of Gray and Bell (28) who recommended a maximum $U_m$ of 53 percent to avoid flat and elongate conditions. Second, the high fines content (15% vs. 0.4%) was the most important factor in reducing flow. Third, the denser gradation ($C_u$ = 29.33 vs. $C_u$ = 2.10 for the control aggregate) made obtaining adequate flow more difficult. Finally, and perhaps least importantly, a higher FM (3.25) indicates a much coarser gradation than ORS (FM = 2.64). Coarser particles are harder to mobilize. Bleeding was not a problem due to the high fines content and denser gradation.

**C. Crushed Sandstone**

Air content rose from 25.7 to 30.4 percent due to more angular aggregate particles ($U_m$ = 47.27 for crushed sandstone vs. $U_m$ = 42.97 for the control aggregate). Flow dropped from 8.5 inches to 6.5 inches. The previously mentioned angularity of the

crushed sandstone particles compared to the control aggregate was certainly a factor. In addition, the crushed sandstone had a much finer gradation as indicated by the comparison of fineness modulii (FM = 2.11 for crushed sandstone compared to FM = 2.64 for the control aggregate). The finer aggregate required more paste to coat and mobilize the particles.

Bleeding did not occur with the initial substitution of crushed sandstone for the control aggregate. However, flow concerns required more paste to mobilize aggregate. Unfortunately the gradation ($U_r$ = 43.67) is much more open than the control aggregate gradation ($U_r$ = 40.19), this would lead to bleeding problems after mixture proportion adjustment. Further, plastic cohesion problems resulted from 58.9 percent of aggregate passing the Number 30 Sieve and being retained on the Number 50 Sieve.

**ZOOM! Mixture Proportion Adjustments for Other Fine Aggregates**

Adjustments were not required for the limestone manufactured sand ZOOM! CLSM. The adjustments and revised proportions for the limestone screenings and crushed sandstone mixtures are shown in Table 18. Plastic properties for the adjusted mixture proportion limestone screenings and crushed sandstone mixtures are shown in Table 19. The research team was not able to satisfy both flow and bleeding requirements for the crushed sandstone ZOOM! CLSM. The research team was able to raise the flow to 7.25 inches without bleeding by increasing the high-range water reducer.

**Table 18. ZOOM! CLSM Adjusted Mixture Proportions for Non-control Aggregates**

| Component | Limestone Screenings | Crushed Sandstone |
|---|---|---|
| Type 1 Portland cement | 350 lbs/CY<br>Control + 50 lbs/CY | 300 lbs/CY |
| Water | 375 lbs/CY<br>Control + 58 lbs/CY | 317 lbs/CY |
| Fine Aggregate (SSD) | 2335 lbs/CY | 2460 lbs/CY |
| Air-entraining agent | 105 oz/CY<br>Control + 35 oz/CY | 70 oz/CY |
| High-range water reducer | 45 oz/CY<br>Control + 15 oz/CY | 91 oz/CY<br>Control + 61 oz/CY |
| Accelerator | 225 oz/CY | 225 oz/CY |

**Table 19. ZOOM! CLSM Plastic Properties for other Aggregates using the Adjusted Mixture Proportions**

| Property | Limestone Screenings | Crushed Sandstone | Requirement |
|---|---|---|---|
| Flow (inches) | 9.50 | 7.25 | 8.75 minimum |
| Bleed Time (min) | No Bleeding | No Bleeding | Little or no bleeding |
| Shrinkage | No Shrinkage | No Shrinkage | Little or no shrinkage |
| Air Content (%) | 22.0 | 26.4 | 20 to 30 preferred |
| Unit Weight (pcf) | 110.6 | 104.8 | No requirement |
| Meet Requirements? | Yes | No, low flow | |

**ZOOM! Field Demonstration Results and Analysis**

Field demonstrations of ZOOM! CLSM were held in Nashville, Knoxville, and Algood, Tennessee using fine aggregate commonly used for PCC in the area or limestone screenings. Each field demonstration consisted of one or more trench (approximately 3 feet wide, 3.5 feet deep and 9 feet long) placements using the local fine aggregate(s). Testing of the ZOOM! CLSM was conducted at each location and currently available information was distributed to government and industry personnel present.

Figures 10 and 11 show comparisons of compressive strength development for field demonstrations and laboratory ZOOM! CLSM mixtures. Figures 12, 13, and 14 show comparison of flow, air content and time to pass the ball drop test, respectively. Compressive strength specimens were not fabricated at Irving Materials Inc. (IMI) Nashville. Ball drop test data is not available for the limestone screenings ZOOM! CLSM at Algood due to excessive water in the trench precluding ball drop testing.

ZOOM! CLSM met compressive strength development and time of set performance criteria at every field demonstration. However, ZOOM! CLSM made with the Ohio River sand control aggregate failed to achieve the desired flow in the lab and for Nashville Number 1 Trench. In each case, the flow was greater than 8 inches but less than 8.75 inches. Limestone manufactured sand ZOOM! CLSM mixtures failed to fall within the desired air content range in the lab and for Knoxville Number 1 Trench. Neither case adversely affected the other mixture properties enough to cause a failure in compressive strength, set time, or flow.

The effect of fine aggregate type on time of set and compressive strength appeared to be indirect. ZOOM! temperature, air content, PC content, and accelerator dosage appeared to have the greatest effect on set time and compressive strength development. Different types of fine aggregates required different PC and air contents to achieve the desired flow characteristics. The research team suspected that the more rapid compressive strength development of limestone screenings was partially due to acceleration of hydration by the limestone fines; however, the limestone screenings mixture had the highest PC content. Therefore, insufficient data was available in this study to make a determination.

The effect of average air temperature divided by air content on the time to pass the ball drop test is shown in Figure 15. The data for Knoxville Trench 1 is not included in Figure 15 due to the unusually low air content of 8.5 percent. The coefficient of determination was 0.6185 indicating a possible relationship. However, only five data points were available for the correlation. Further, ZOOM! CLSM mixture temperature over time would have been superior to average air temperature, unfortunately that data was not available. Finally, two key factors for time to pass ball drop did not vary in the available data, Portland cement content and accelerator dosage.

**Figure 10. Comparison of Lab and Field Compressive Strength Development for LS Screenings and LS Manufactured Sand Mixtures**

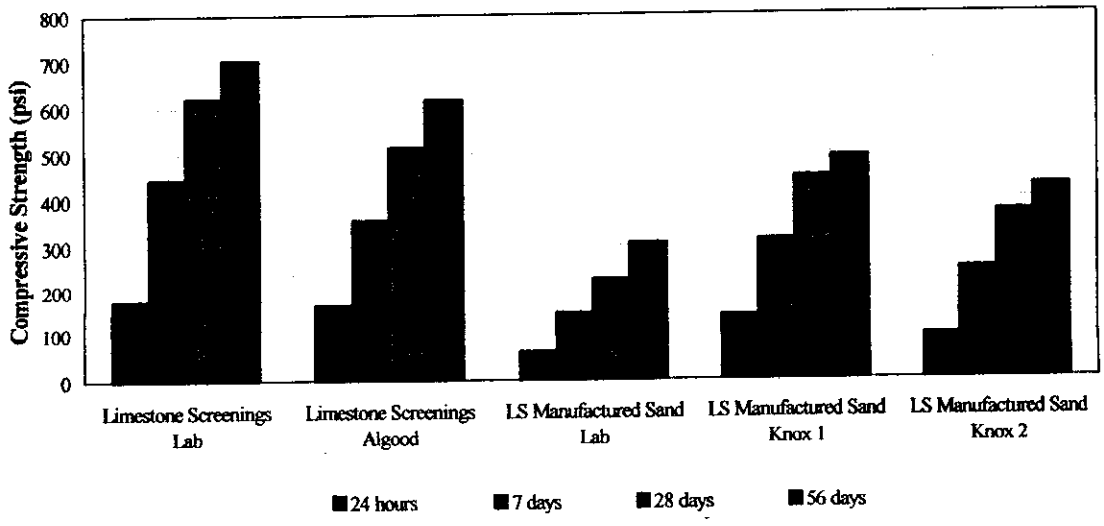


**Figure 11. Comparison of Lab and Field Compressive Strength Development for Ohio River Sand Mixtures**

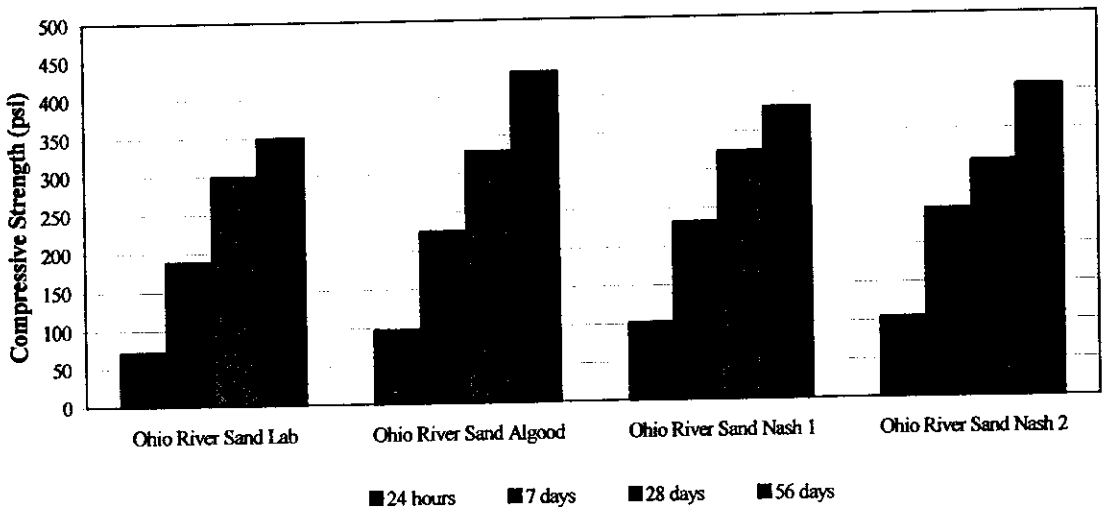



**Figure 12. Comparison of Flow Values**

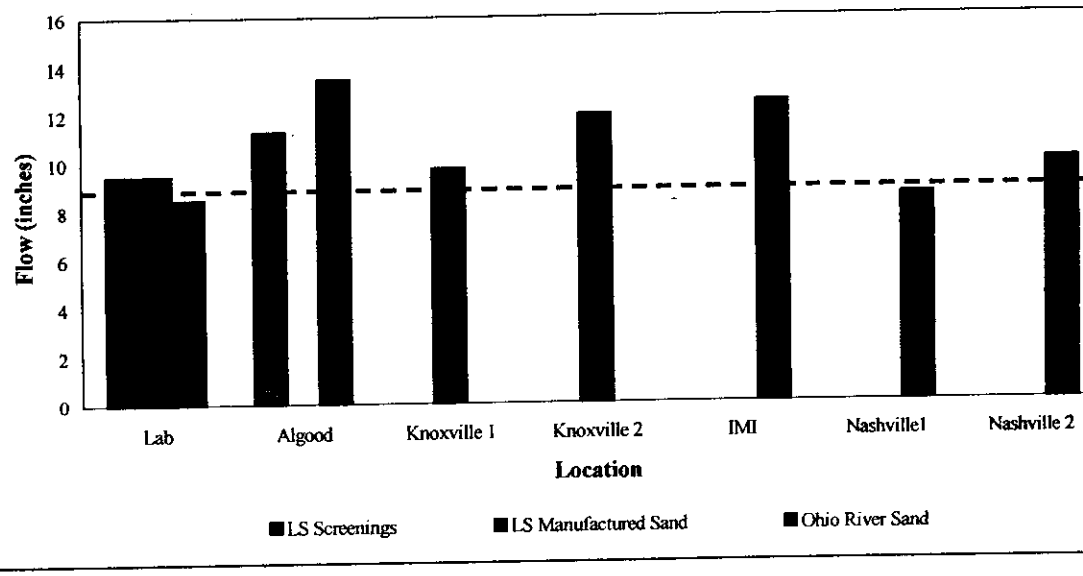


**Figure 13. Comparison of Air Contents**

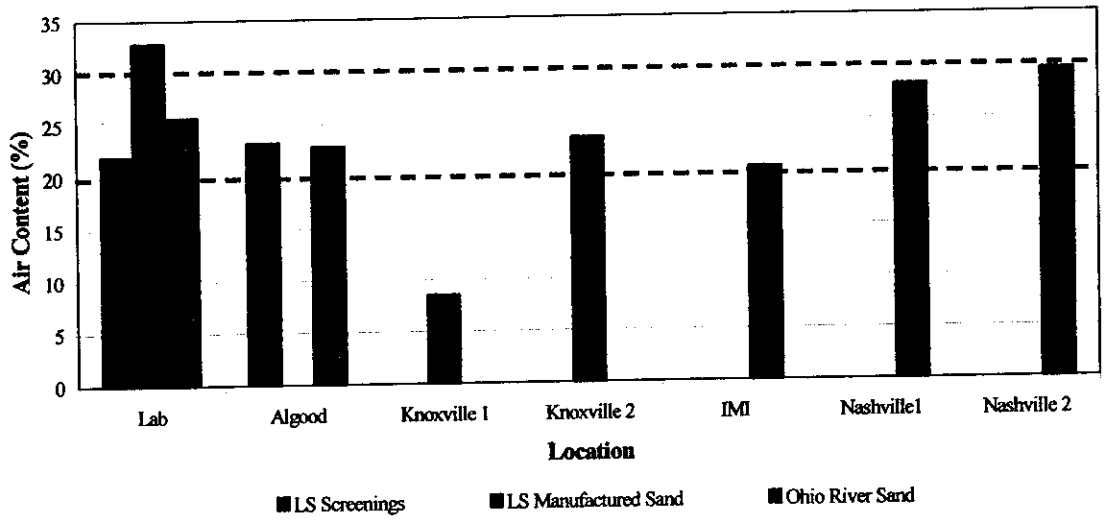



**Figure 14. Comparison of Times to Pass ASTM Ball Drop**

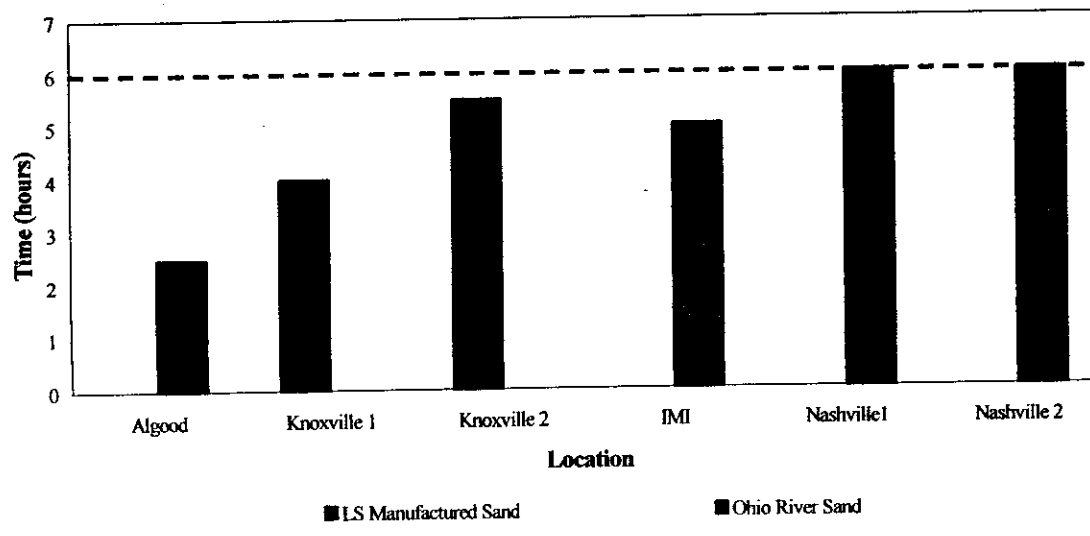
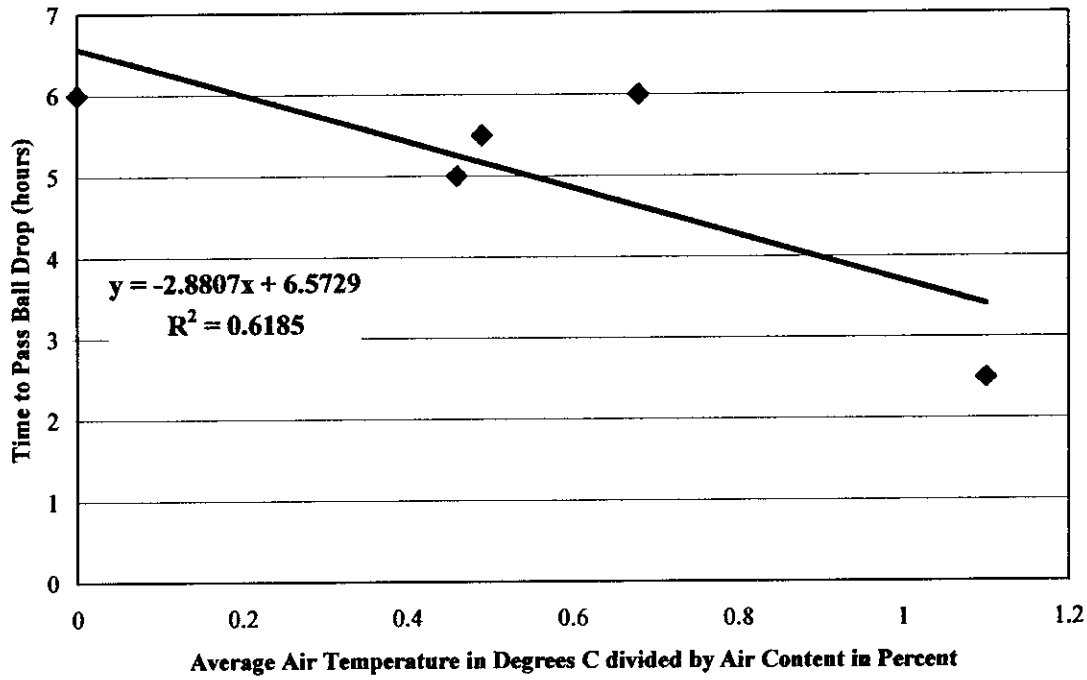


**FIGURE 15. Effect of Average Air Temperature and Air Content on Time to Pass Ball Drop Test**



**ZOOM! Conclusions**

The following conclusions can be drawn from the limited data available in this study:

1) A high flow, rapid-set, non-excavatable CLSM for applications where time was a critical factor can be produced with a wide variety of Tennessee fine aggregates.
2) Fine aggregate properties such as gradation and angularity dictate mixture proportions required to achieve flow, air content, and bleeding characteristics of CLSM.
3) Average air temperature was inversely proportional to time of suitability for load application.
4) CLSM air content was directly proportional to time of suitability for load application.

**ZOOM! Technology Transfer**

Technology transfer was accomplished by preparing a minimum of 1000 copies of a CD-ROM containing the project results and a model specification for ZOOM!. The CD-ROMs were distributed by holding four seminars (Nashville 7/16/03 and Knoxville 7/17/03 in Tennessee and Frankfort 8/13/03 and Owensboro 8/14/03 in Kentucky) for ready mix producers, municipal and state specifying officials. The CD-ROMs were also to be distributed by TRMCA and KRMCA. The CD-ROMs and associated seminars were funded by KRMCA. Additional technology transfer occurred through a presentation entitled "Effect of Fine Aggregate Type on CLSM Properties" at the International Center

for Aggregate Research 11th Annual Symposium on Aggregates: Asphalt Concrete, Portland Cement Concrete, Bases, and Fines in Austin, Texas in April 2003. An accompanying paper was published in the ICAR symposium proceedings. Further technology transfer is planned through a presentation at the ASTM Symposium on Innovations in Controlled Low-Strength Material (Flowable Fill) on June 19, 2003 in Denver, Colorado. A paper entitled "ZOOM!" was submitted for possible publication in ASTM STP 1459 (at the discretion of the ASTM Committee on Publications).

**ZOOM! Acknowledgements**

The authors wish to gratefully acknowledge the support of the Tennessee Department of Transportation and the Tennessee Ready Mixed Concrete Association. We would especially like to thank IMI of Nashville, TN, Rogers Group Inc. of Algood, TN, Plateau Ready Mix of Cookeville, TN, Rinker Materials of Knoxville, TN, and Master Builders Technologies Inc. of Tennessee. The authors sincerely appreciate the technical assistance provided by Denny Lind, Larry Clouse, Brian Egan, Steve Hall, Ralph Beard, Matthew Tays, Shane Beasley, Rob Bailey, Kim Couch, Jamie Waller, Joe Fowler, Phil Johnson, Landon Deel, Alan Sparkman, Jay Coleman, Rod Gamble, and Dale Cathey. The authors gratefully acknowledge the financial support, financial project management, and computer assistance of the TTU Center for Electric Power

**ZOOM! Disclaimer**

The opinions, findings, and conclusions expressed here are those of the authors and not necessarily those of the Tennessee Department of Transportation or the Tennessee Ready Mixed Concrete Association.

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# APPENDIX A

**Table A1. 7-Day EFF Compressive Strength Data**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 1 KTC 30/300 | 50 | 3.98 | 4.66 | 7.60 | 130.6 | 131.6 |
| | 67 | 5.33 | | 7.71 | 132.6 | |
| | -- | -- | | -- | -- | |
| Mixture 2 30/370 | 77 | 6.13 | 5.60 | 7.81 | 134.3 | 133.8 |
| | 66 | 5.25 | | 7.73 | 132.9 | |
| | 68 | 5.41 | | 7.80 | 134.2 | |
| Mixture 3 30/440 | 89 | 7.08 | 7.37 | 7.56 | 130.0 | 129.4 |
| | 97 | 7.72 | | 7.54 | 129.6 | |
| | 92 | 7.32 | | 7.49 | 128.8 | |
| Mixture 4 45/300 | 107 | 8.51 | 8.89 | 7.68 | 132.0 | 131.9 |
| | 122 | 9.71 | | 7.72 | 132.6 | |
| | 106 | 8.44 | | 7.63 | 131.2 | |
| 5 TRMCA 45/370 | 88 | 7.00 | 7.98 | 7.63 | 131.1 | 130.6 |
| | 110 | 8.75 | | 7.57 | 130.0 | |
| | 103 | 8.20 | | 7.60 | 130.6 | |
| Mixture 6 45/440 | 211 | 16.79 | 16.55 | 7.69 | 132.2 | 132.1 |
| | 228 | 18.14 | | 7.66 | 131.7 | |
| | 185 | 14.72 | | 7.70 | 132.4 | |
| Mixture 7 60/300 | 115 | 9.15 | 10.00 | 7.49 | 128.8 | 128.7 |
| | 133 | 10.58 | | 7.46 | 128.2 | |
| | 129 | 10.27 | | 7.50 | 129.0 | |
| Mixture 8 60/370 | 221 | 17.59 | 17.08 | 7.61 | 130.7 | 130.1 |
| | 209 | 16.63 | | 7.53 | 129.4 | |
| | 214 | 17.03 | | 7.57 | 130.1 | |
| 9 TTU CAP 60/440 | 282 | 22.44 | 27.64 | 7.61 | 130.7 | 131.0 |
| | 392 | 31.19 | | 7.64 | 131.3 | |
| | 368 | 29.28 | | 7.63 | 131.1 | |
| Mixture 10 45/370 High Carbon Ash | 264 | 21.01 | 21.80 | 7.41 | 127.3 | 127.5 |
| | 284 | 22.60 | | 7.43 | 127.7 | |
| | 225 | 17.90 | | 7.42 | 127.5 | |

-- Sample did not survive de-molding

**Table A1. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| Mixture 11 60/370 High Carbon Ash | 335 | 26.66 | 26.87 | 7.43 | 127.6 | 127.4 |
| | 318 | 25.31 | | 7.38 | 126.9 | |
| | 360 | 28.65 | | 7.43 | 127.7 | |
| Mixture 12 45/440 High Carbon Ash | 134 | 10.66 | 11.86 | 7.46 | 128.2 | 128.5 |
| | 146 | 11.62 | | 7.45 | 128.1 | |
| | 167 | 13.29 | | 7.52 | 129.3 | |
| Mixture 13 60/440 High Carbon Ash | 329 | 26.18 | 27.59 | 7.49 | 128.7 | 127.7 |
| | 400 | 31.83 | | 7.32 | 125.8 | |
| | 311 | 24.75 | | 7.48 | 128.6 | |
| Mixture 14 45/510 High Carbon Ash | 282 | 22.44 | 23.13 | 7.55 | 129.7 | 128.5 |
| | 321 | 25.54 | | 7.44 | 127.8 | |
| | 269 | 21.41 | | 7.45 | 128.1 | |
| Mixture 15 60/510 High Carbon Ash | 536 | 42.65 | 47.03 | 7.36 | 126.5 | 125.0 |
| | 605 | 48.14 | | 7.25 | 124.6 | |
| | 632 | 50.29 | | 7.22 | 124.1 | |
| 16 Manufactured Limestone Sand 45/370 | 252 | 20.05 | 20.40 | 7.49 | 128.7 | 128.3 |
| | 285 | 22.68 | | 7.43 | 127.7 | |
| | 232 | 18.46 | | 7.48 | 128.6 | |
| 17 Crushed Sandstone Sand 45/370 | 175 | 13.93 | 12.77 | 7.20 | 123.7 | 125.7 |
| | 146 | 11.62 | | 7.37 | 126.6 | |
| | 148 | 11.78 | | 7.37 | 126.8 | |
| 18 Masonry Sand 45/370 | 182 | 14.48 | 18.50 | 7.21 | 123.9 | 124.8 |
| | 283 | 22.52 | | 7.29 | 125.3 | |
| | 325 | 25.86 | | 7.28 | 125.1 | |
| 19 Limestone Screenings 45/370 | 285 | 22.68 | 22.94 | 7.75 | 133.2 | 132.7 |
| | 293 | 23.32 | | 7.71 | 132.6 | |
| | 287 | 22.84 | | 7.69 | 132.2 | |

**Table A1. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 22 TDOT 100/250 | 255 | 20.29 | 20.96 | 7.40 | 127.2 | 126.3 |
| | 239 | 19.02 | | 7.35 | 126.3 | |
| | 296 | 23.55 | | 7.29 | 125.2 | |
| 23 MBT MB AE 90 | 148 | 11.78 | 10.45 | 5.55 | 95.4 | 94.9 |
| | 126 | 10.03 | | 5.50 | 94.5 | |
| | 120 | 9.55 | | 5.51 | 94.7 | |
| 24 W.R. Grace Darafill | 386 | 30.72 | 31.59 | 6.11 | 105.0 | 104.5 |
| | 406 | 32.31 | | 6.10 | 104.9 | |
| | 399 | 31.75 | | 6.03 | 103.6 | |
| 25 MBT Rheofill Limestone Manufactured Sand | 145 | 11.54 | 11.14 | 5.84 | 100.4 | 100.4 |
| | 138 | 10.98 | | 5.87 | 100.8 | |
| | 137 | 10.90 | | 5.81 | 99.9 | |

**Table A2. 28-Day EFF Compressive Strength Data**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 1 KTC 30/300 | 74 | 5.89 | 5.73 | 7.42 | 127.5 | 128.2 |
| | 67 | 5.33 | | 7.53 | 129.4 | |
| | 75 | 5.97 | | 7.44 | 127.8 | |
| Mixture 2 30/370 | 115 | 9.15 | 10.24 | 7.36 | 126.4 | 129.9 |
| | 142 | 11.30 | | 7.75 | 133.1 | |
| | 129 | 10.27 | | 7.58 | 130.2 | |
| Mixture 3 30/440 | 122 | 9.71 | 12.60 | 7.36 | 126.6 | 127.7 |
| | 168 | 13.37 | | 7.45 | 128.1 | |
| | 185 | 14.72 | | 7.47 | 128.4 | |
| Mixture 4 45/300 | 241 | 19.18 | 19.60 | 7.56 | 129.9 | 129.9 |
| | 263 | 20.93 | | 7.57 | 130.2 | |
| | 235 | 18.70 | | 7.54 | 129.6 | |
| 5 TRMCA 45/370 | 187 | 14.88 | 16.74 | 7.57 | 130.2 | 130.3 |
| | 222 | 17.67 | | 7.59 | 130.4 | |
| | 222 | 17.67 | | 7.58 | 130.3 | |
| Mixture 6 45/440 | 248 | 19.74 | 19.81 | 7.57 | 130.1 | 129.8 |
| | 226 | 17.98 | | 7.56 | 129.9 | |
| | 273 | 21.72 | | 7.53 | 129.4 | |
| Mixture 7 60/300 | 230 | 18.30 | 17.32 | 7.42 | 127.5 | 127.6 |
| | 216 | 17.19 | | 7.45 | 128.1 | |
| | 207 | 16.47 | | 7.41 | 127.3 | |
| Mixture 8 60/370 | 353 | 28.09 | 26.87 | 7.47 | 128.5 | 128.3 |
| | 319 | 25.39 | | 7.47 | 128.4 | |
| | 341 | 27.14 | | 7.45 | 128.0 | |
| 9 TTU CAP 60/440 | 564 | 44.88 | 39.55 | 7.65 | 131.4 | 131.4 |
| | 433 | 34.46 | | 7.70 | 132.3 | |
| | 494 | 39.31 | | 7.60 | 130.6 | |
| Mixture 10 45/370 High Carbon Ash | 442 | 35.17 | 34.09 | 7.45 | 128.1 | 127.8 |
| | 489 | 38.91 | | 7.42 | 127.5 | |
| | 354 | 28.17 | | 7.43 | 127.7 | |

**Table A2. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| Mixture 11 60/370 High Carbon Ash | 525 | 41.78 | 40.56 | 7.45 | 128.1 | 127.9 |
| | 552 | 43.93 | | 7.46 | 128.1 | |
| | 452 | 35.97 | | 7.42 | 127.6 | |
| Mixture 12 45/440 High Carbon Ash | 219 | 17.43 | 19.84 | 7.43 | 127.7 | 128.5 |
| | 265 | 21.09 | | 7.47 | 128.4 | |
| | 264 | 21.01 | | 7.54 | 129.5 | |
| Mixture 13 60/440 High Carbon Ash | 359 | 28.57 | 30.72 | 7.44 | 127.8 | 127.1 |
| | 299 | 23.79 | | 7.42 | 127.5 | |
| | 500 | 39.79 | | 7.33 | 126.0 | |
| Mixture 14 45/510 High Carbon Ash | 366 | 29.13 | 28.75 | 7.45 | 128.0 | 128.6 |
| | 365 | 29.05 | | 7.42 | 127.6 | |
| | 353 | 28.09 | | 7.57 | 130.1 | |
| Mixture 15 60/510 High Carbon Ash | 811 | 64.54 | 58.65 | 7.24 | 124.5 | 126.5 |
| | 694 | 55.23 | | 7.40 | 127.2 | |
| | 706 | 56.18 | | 7.44 | 127.8 | |
| 16 Manufactured Limestone Sand 45/370 | 628 | 49.97 | 48.60 | 7.54 | 129.6 | 130.1 |
| | 603 | 47.99 | | 7.56 | 129.9 | |
| | 601 | 47.83 | | 7.60 | 130.7 | |
| 17 Crushed Sandstone Sand 45/370 | 314 | 24.99 | 24.35 | 7.30 | 125.5 | 123.9 |
| | 298 | 23.71 | | 7.21 | 123.9 | |
| | 275 | 21.88 | | 7.12 | 122.4 | |
| 18 Masonry Sand 45/370 | 529 | 42.10 | 47.67 | 7.32 | 125.8 | 125.1 |
| | 669 | 53.24 | | 7.24 | 124.4 | |
| | 415 | 33.02 | | 7.27 | 125.0 | |
| 19 Limestone Screenings 45/370 | 741 | 58.97 | 57.80 | 7.73 | 132.9 | 133.1 |
| | 690 | 54.91 | | 7.79 | 133.9 | |
| | 748 | 59.52 | | 7.70 | 132.3 | |

**Table A2. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 22 TDOT 100/250 | 419 | 33.34 | 40.08 | 7.32 | 125.8 | 127.3 |
| | 500 | 39.79 | | 7.33 | 125.9 | |
| | 592 | 47.11 | | 7.56 | 130.0 | |
| 23 MBT MB AE 90 | 197 | 15.68 | 15.68 | 5.37 | 92.4 | 92.4 |
| | -- | -- | | -- | -- | |
| | -- | -- | | -- | -- | |
| 24 W.R. Grace Darafill | 368 | 29.28 | 35.49 | 5.92 | 101.8 | 102.6 |
| | 524 | 41.70 | | 6.00 | 103.2 | |
| | 446 | 35.49 | | 5.98 | 102.9 | |
| 25 MBT Rheofill Limestone Manufactured Sand | 218 | 17.35 | 16.68 | 5.90 | 101.4 | 100.7 |
| | 213 | 16.95 | | 5.93 | 101.8 | |
| | 198 | 15.76 | | 5.76 | 99.0 | |

-- Sample did not survive de-molding

**Table A3. 63-Day EFF Compressive Strength Data**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 1 KTC 30/300 | 95 | 7.56 | 7.60 | 7.31 | 125.7 | 127.7 |
| | 96 | 7.64 | | 7.47 | 128.4 | |
| | 100 | 7.96 | | 7.51 | 129.1 | |
| Mixture 2 30/370 | 137 | 10.90 | 11.88 | 7.32 | 125.8 | 127.0 |
| | 148 | 11.78 | | 7.32 | 125.8 | |
| | 163 | 12.97 | | 7.52 | 129.3 | |
| Mixture 3 30/440 | 216 | 17.19 | 19.71 | 7.04 | 121.0 | 123.8 |
| | 269 | 21.41 | | 7.33 | 126.0 | |
| | 258 | 20.53 | | 7.23 | 124.3 | |
| Mixture 4 45/300 | 262 | 20.85 | 23.95 | 7.31 | 125.7 | 126.8 |
| | 275 | 21.88 | | 7.41 | 127.4 | |
| | 366 | 29.13 | | 7.41 | 127.4 | |
| 5 TRMCA 45/370 | 264 | 21.01 | 18.20 | 7.15 | 122.9 | 125.3 |
| | 199 | 15.84 | | 7.41 | 127.4 | |
| | 223 | 17.75 | | 7.31 | 125.7 | |
| Mixture 6 45/440 | 384 | 30.56 | 37.06 | 7.32 | 125.8 | 130.2 |
| | 488 | 38.83 | | 7.68 | 131.9 | |
| | 525 | 41.78 | | 7.73 | 132.9 | |
| Mixture 7 60/300 | 530 | 42.18 | 37.67 | 7.31 | 125.7 | 126.2 |
| | 391 | 31.11 | | 7.40 | 127.2 | |
| | 499 | 39.71 | | 7.32 | 125.8 | |
| Mixture 8 60/370 | 676 | 53.79 | 51.73 | 7.23 | 124.2 | 125.2 |
| | 666 | 53.00 | | 7.30 | 125.4 | |
| | 608 | 48.38 | | 7.32 | 125.9 | |
| 9 TTU CAP 60/440 | 795 | 63.26 | 77.96 | 7.36 | 126.5 | 127.3 |
| | 1155 | 91.91 | | 7.44 | 127.8 | |
| | 989 | 78.70 | | 7.41 | 127.4 | |
| Mixture 10 45/370 High Carbon Ash | 560 | 44.56 | 44.88 | 7.35 | 126.3 | 126.6 |
| | 436 | 34.70 | | 7.32 | 125.8 | |
| | 696 | 55.39 | | 7.42 | 127.6 | |

**Table A3. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| Mixture 11 60/370 High Carbon Ash | 659 | 52.44 | 54.51 | 7.32 | 125.7 | 125.6 |
| | 753 | 59.92 | | 7.33 | 125.9 | |
| | 643 | 51.17 | | 7.27 | 125.0 | |
| Mixture 12 45/440 High Carbon Ash | 313 | 24.91 | 23.08 | 7.44 | 128.0 | 127.2 |
| | 289 | 23.00 | | 7.40 | 127.3 | |
| | 268 | 21.33 | | 7.35 | 126.4 | |
| Mixture 13 60/440 High Carbon Ash | 596 | 47.43 | 46.63 | 7.49 | 128.7 | 127.1 |
| | 601 | 47.83 | | 7.44 | 127.9 | |
| | 561 | 44.64 | | 7.26 | 124.8 | |
| Mixture 14 45/510 High Carbon Ash | 452 | 35.97 | 35.17 | 7.23 | 124.3 | 125.3 |
| | 432 | 34.38 | | 7.34 | 126.2 | |
| | -- | -- | | -- | -- | |
| Mixture 15 60/510 High Carbon Ash | 873 | 69.47 | 76.42 | 6.98 | 120.0 | 121.4 |
| | 1011 | 80.45 | | 7.09 | 121.8 | |
| | 997 | 79.34 | | 7.12 | 122.3 | |
| 16 Manufactured Limestone Sand 45/370 | 886 | 70.51 | 64.33 | 7.55 | 129.8 | 129.9 |
| | 906 | 72.10 | | 7.50 | 128.9 | |
| | 633 | 50.37 | | 7.63 | 131.1 | |
| 17 Crushed Sandstone Sand 45/370 | 724 | 57.61 | 51.84 | 7.24 | 124.5 | 122.1 |
| | 579 | 46.08 | | 6.86 | 118.0 | |
| | 591 | 47.03 | | 7.20 | 123.7 | |
| 18 Masonry Sand 45/370 | 480 | 38.20 | 60.68 | 6.86 | 117.8 | 123.1 |
| | 1045 | 83.16 | | 7.38 | 126.9 | |
| | 658 | 52.36 | | 7.25 | 124.7 | |
| 19 Limestone Screenings 45/370 | 995 | 79.18 | 82.71 | 7.66 | 131.7 | 131.1 |
| | 1087 | 86.50 | | 7.61 | 130.7 | |
| | 1036 | 82.44 | | 7.61 | 130.7 | |

-- Sample did not survive de-molding

**Table A3. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 22 TDOT 100/250 | 703 | 55.94 | 68.38 | 7.17 | 123.2 | 125.3 |
| | 863 | 68.68 | | 7.33 | 126.0 | |
| | 1012 | 80.53 | | 7.37 | 126.7 | |
| 23 MBT MB AE 90 | 225 | 17.90 | 18.75 | 5.18 | 89.0 | 92.2 |
| | 247 | 19.66 | | 5.45 | 93.7 | |
| | 235 | 18.70 | | 5.47 | 94.0 | |
| 24 W.R. Grace Darafill | 526 | 41.86 | 45.44 | 5.94 | 102.1 | 102.9 |
| | 618 | 49.18 | | 6.04 | 103.8 | |
| | 569 | 45.28 | | 5.99 | 102.9 | |
| 25 MBT Rheofill Limestone Manufactured Sand | 238 | 18.94 | 18.09 | 5.71 | 98.1 | 98.4 |
| | 227 | 18.06 | | 5.81 | 99.8 | |
| | 217 | 17.27 | | 5.66 | 97.3 | |

**Table A4. 98-Day EFF Compressive Strength Data**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 1 KTC 30/300 | 132 | 10.50 | 8.86 | 7.11 | 122.2 | 124.4 |
| | 113 | 8.99 | | 7.17 | 123.3 | |
| | 89 | 7.08 | | 7.42 | 127.6 | |
| Mixture 2 30/370 | 221 | 17.59 | 14.93 | 7.47 | 128.4 | 126.7 |
| | 159 | 12.65 | | 7.35 | 126.4 | |
| | 183 | 14.56 | | 7.29 | 125.2 | |
| Mixture 3 30/440 | 219 | 17.43 | 20.16 | 7.08 | 121.6 | 122.9 |
| | 299 | 23.79 | | 7.21 | 123.9 | |
| | 242 | 19.26 | | 7.17 | 123.2 | |
| Mixture 4 45/300 | 482 | 38.36 | 39.76 | 7.34 | 126.1 | 126.4 |
| | 510 | 40.58 | | 7.37 | 126.7 | |
| | 507 | 40.35 | | 7.35 | 126.4 | |
| 5 TRMCA 45/370 | 271 | 21.57 | 20.56 | 7.14 | 122.7 | 123.0 |
| | 229 | 18.22 | | 7.16 | 123.0 | |
| | 275 | 21.88 | | 7.17 | 123.2 | |
| Mixture 6 45/440 | 441 | 35.09 | 38.17 | 7.13 | 122.6 | 122.7 |
| | 619 | 49.26 | | 7.24 | 124.5 | |
| | 379 | 30.16 | | 7.04 | 121.1 | |
| Mixture 7 60/300 | 727 | 57.85 | 56.00 | 7.16 | 123.0 | 123.9 |
| | 668 | 53.16 | | 7.25 | 124.5 | |
| | 716 | 56.98 | | 7.22 | 124.1 | |
| Mixture 8 60/370 | 685 | 54.51 | 60.16 | 7.20 | 123.8 | 123.6 |
| | 809 | 64.38 | | 7.19 | 123.6 | |
| | 774 | 61.59 | | 7.18 | 123.4 | |
| 9 TTU CAP 60/440 | 1591 | 126.61 | 107.83 | 7.26 | 124.8 | 124.3 |
| | 1231 | 97.96 | | 7.33 | 126.1 | |
| | 1243 | 98.91 | | 7.10 | 122.0 | |
| Mixture 10 45/370 High Carbon Ash | 519 | 41.30 | 41.14 | 7.22 | 124.1 | 123.6 |
| | 409 | 32.55 | | 7.12 | 122.3 | |
| | 623 | 49.58 | | 7.24 | 124.4 | |

**Table A4. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| Mixture 11 60/370 High Carbon Ash | 1116 | 88.81 | 80.82 | 7.13 | 122.5 | 120.0 |
| | 845 | 67.24 | | 6.99 | 120.2 | |
| | 1086 | 86.42 | | 6.82 | 117.2 | |
| Mixture 12 45/440 High Carbon Ash | 278 | 22.12 | 23.93 | 7.21 | 123.8 | 125.0 |
| | 334 | 26.58 | | 7.41 | 127.3 | |
| | 290 | 23.08 | | 7.21 | 123.9 | |
| Mixture 13 60/440 High Carbon Ash | 583 | 46.39 | 42.65 | 7.25 | 124.5 | 124.4 |
| | 525 | 41.78 | | 7.22 | 124.1 | |
| | 500 | 39.79 | | 7.24 | 124.5 | |
| Mixture 14 45/510 High Carbon Ash | 552 | 43.93 | 37.80 | 7.12 | 122.4 | 123.4 |
| | 447 | 35.57 | | 7.25 | 124.7 | |
| | 426 | 33.90 | | 7.17 | 123.2 | |
| Mixture 15 60/510 High Carbon Ash | 958 | 76.24 | 88.60 | 7.17 | 123.3 | 122.3 |
| | 1135 | 90.32 | | 6.99 | 120.2 | |
| | 1247 | 99.23 | | 7.19 | 123.5 | |
| 16 Manufactured Limestone Sand 45/370 | 998 | 79.42 | 85.25 | 7.44 | 127.9 | 127.1 |
| | 1120 | 89.13 | | 7.37 | 126.8 | |
| | 1096 | 87.22 | | 7.38 | 126.8 | |
| 17 Crushed Sandstone Sand 45/370 | 958 | 76.24 | 78.66 | 7.04 | 121.0 | 122.1 |
| | 1019 | 81.09 | | 7.25 | 124.5 | |
| | 689 | 54.83 | | 7.03 | 120.8 | |
| 18 Masonry Sand 45/370 | 697 | 55.47 | 71.94 | 6.74 | 115.8 | 120.6 |
| | 1111 | 88.41 | | 7.23 | 124.3 | |
| | 1149 | 91.43 | | 7.08 | 121.7 | |
| 19 Limestone Screenings 45/370 | 1169 | 93.03 | 91.59 | 7.55 | 129.8 | 129.5 |
| | 1163 | 92.55 | | 7.62 | 131.0 | |
| | 1121 | 89.21 | | 7.44 | 127.8 | |

**Table A4. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 22 TDOT 100/250 | 1301 | 103.53 | 97.54 | 7.22 | 124.0 | 123.2 |
| | 1574 | 125.25 | | 7.23 | 124.3 | |
| | 802 | 63.82 | | 7.06 | 121.3 | |
| 23 MBT MB AE 90 | 281 | 22.36 | 22.28 | 5.44 | 93.6 | 93.8 |
| | 295 | 23.48 | | 5.55 | 95.4 | |
| | 264 | 21.01 | | 5.37 | 92.3 | |
| 24 W.R. Grace Darafill | 671 | 53.40 | 50.35 | 5.84 | 100.4 | 102.9 |
| | 544 | 43.29 | | 6.06 | 104.1 | |
| | 683 | 54.35 | | 6.07 | 104.3 | |
| 25 MBT Rheofill Limestone Manufactured Sand | 236 | 18.78 | 19.68 | 5.78 | 99.3 | 97.6 |
| | 248 | 19.74 | | 5.59 | 96.2 | |
| | 258 | 20.53 | | 5.66 | 97.3 | |

**Table A5. 140-Day EFF Compressive Strength Data**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 1 KTC 30/300 | 99 | 7.88 | 8.97 | 7.06 | 121.3 | 121.4 |
| | 103 | 8.20 | | 6.84 | 117.6 | |
| | 136 | 10.82 | | 7.29 | 125.3 | |
| Mixture 2 30/370 | 189 | 15.04 | 13.00 | 7.35 | 126.3 | 120.5 |
| | 114 | 9.07 | | 6.87 | 118.1 | |
| | 187 | 14.88 | | 6.82 | 117.1 | |
| Mixture 3 30/440 | 263 | 20.93 | 18.94 | 7.10 | 122.0 | 118.8 |
| | 228 | 18.14 | | 6.75 | 116.1 | |
| | 223 | 17.75 | | 6.89 | 118.5 | |
| Mixture 4 45/300 | 544 | 43.29 | 36.58 | 6.84 | 117.6 | 118.7 |
| | 455 | 36.21 | | 7.05 | 121.2 | |
| | 380 | 30.24 | | 6.82 | 117.3 | |
| 5 TRMCA 45/370 | 364 | 28.97 | 24.43 | 7.03 | 120.8 | 119.2 |
| | 272 | 21.65 | | 6.82 | 117.2 | |
| | 285 | 22.68 | | 6.96 | 119.7 | |
| Mixture 6 45/440 | 727 | 57.85 | 55.76 | 7.16 | 123.1 | 124.2 |
| | 736 | 58.57 | | 7.17 | 123.3 | |
| | 639 | 50.85 | | 7.35 | 126.3 | |
| Mixture 7 60/300 | 739 | 58.81 | 66.26 | 7.14 | 122.7 | 123.2 |
| | 789 | 62.79 | | 7.11 | 122.2 | |
| | 970 | 77.19 | | 7.25 | 124.6 | |
| Mixture 8 60/370 | 920 | 73.21 | 69.26 | 7.12 | 122.4 | 122.5 |
| | 830 | 66.05 | | 7.18 | 123.5 | |
| | 861 | 68.52 | | 7.09 | 121.8 | |
| 9 TTU CAP 60/440 | 1143 | 90.96 | 110.80 | 7.06 | 121.4 | 123.9 |
| | 1613 | 128.36 | | 7.26 | 124.8 | |
| | 1421 | 113.08 | | 7.31 | 125.7 | |
| Mixture 10 45/370 High Carbon Ash | 679 | 54.03 | 67.77 | 7.20 | 123.8 | 119.0 |
| | 1067 | 84.91 | | 6.78 | 116.5 | |
| | 809 | 64.38 | | 6.79 | 116.7 | |

**Table A5. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| Mixture 11 60/370 High Carbon Ash | 1384 | 110.14 | 108.38 | 6.87 | 118.1 | 120.3 |
| | 1386 | 110.29 | | 6.97 | 119.8 | |
| | 1316 | 104.72 | | 7.15 | 123.0 | |
| Mixture 12 45/440 High Carbon Ash | 288 | 22.92 | 22.71 | 7.18 | 123.5 | 122.3 |
| | 286 | 22.76 | | 7.11 | 122.3 | |
| | 282 | 22.44 | | 7.04 | 121.1 | |
| Mixture 13 60/440 High Carbon Ash | 838 | 66.69 | 62.95 | 6.85 | 117.8 | 121.5 |
| | 726 | 57.77 | | 7.21 | 124.0 | |
| | 809 | 64.38 | | 7.15 | 122.8 | |
| Mixture 14 45/510 High Carbon Ash | 647 | 51.49 | 53.56 | 7.04 | 121.0 | 121.2 |
| | 644 | 51.25 | | 7.07 | 121.6 | |
| | 728 | 57.93 | | 7.04 | 121.1 | |
| Mixture 15 60/510 High Carbon Ash | 1502 | 119.53 | 101.65 | 7.06 | 121.3 | 121.8 |
| | 1385 | 110.21 | | 7.10 | 122.1 | |
| | 945 | 75.20 | | 7.09 | 121.9 | |
| 16 Manufactured Limestone Sand 45/370 | 1086 | 86.42 | 80.98 | 7.37 | 126.6 | 127.6 |
| | 943 | 75.04 | | 7.41 | 127.3 | |
| | 1024 | 81.49 | | 7.50 | 129.0 | |
| 17 Crushed Sandstone Sand 45/370 | 1128 | 89.76 | 79.14 | 6.64 | 114.1 | 116.5 |
| | 861 | 68.52 | | 6.98 | 119.9 | |
| | 1153 | 91.75 | | 6.72 | 115.4 | |
| 18 Masonry Sand 45/370 | 1270 | 101.06 | 113.36 | 7.07 | 121.5 | 120.2 |
| | 1579 | 125.65 | | 6.74 | 115.9 | |
| | 1354 | 107.75 | | 7.17 | 123.2 | |
| 19 Limestone Screenings 45/370 | 1155 | 91.91 | 98.97 | 7.53 | 129.4 | 129.0 |
| | 1184 | 94.22 | | 7.60 | 130.6 | |
| | 1392 | 110.77 | | 7.38 | 126.9 | |

**Table A5. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 22 TDOT 100/250 | 1843 | 146.66 | 141.14 | 6.99 | 120.1 | 121.3 |
| | 1951 | 155.26 | | 7.00 | 120.3 | |
| | 1527 | 121.51 | | 7.18 | 123.4 | |
| 23 MBT MB AE 90 | 294 | 23.40 | 23.77 | 5.28 | 90.8 | 89.4 |
| | 342 | 27.22 | | 5.14 | 88.3 | |
| | 260 | 20.69 | | 5.18 | 89.1 | |
| 24 W.R. Grace Darafill | 595 | 47.35 | 51.01 | 5.90 | 101.4 | 101.7 |
| | 676 | 53.79 | | 5.97 | 102.7 | |
| | 652 | 51.88 | | 5.87 | 101.0 | |
| 25 MBT Rheofill Limestone Manufactured Sand | 300 | 23.87 | 23.63 | 5.37 | 92.3 | 93.9 |
| | 295 | 23.48 | | 5.52 | 94.8 | |
| | 296 | 23.55 | | 5.50 | 94.5 | |

**Table A6. 182-Day EFF Compressive Strength Data**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 1 KTC 30/300 | 140 | 11.14 | 9.47 | 7.20 | 123.8 | 118.9 |
| | 99 | 7.88 | | 6.87 | 118.1 | |
| | 118 | 9.39 | | 6.67 | 114.7 | |
| Mixture 2 30/370 | 206 | 16.39 | 15.09 | 7.15 | 122.9 | 127.7 |
| | 192 | 15.28 | | 7.53 | 129.5 | |
| | 171 | 13.61 | | 7.61 | 130.8 | |
| Mixture 3 30/440 | 242 | 19.26 | 21.11 | 6.82 | 117.2 | 118.8 |
| | 293 | 23.32 | | 6.86 | 118.0 | |
| | 261 | 20.77 | | 7.05 | 121.1 | |
| Mixture 4 45/300 | 502 | 39.95 | 45.31 | 7.05 | 121.1 | 121.5 |
| | 723 | 57.53 | | 7.25 | 124.6 | |
| | 483 | 38.44 | | 6.90 | 118.6 | |
| 5 TRMCA 45/370 | 465 | 37.00 | 34.88 | 6.87 | 118.1 | 119.1 |
| | 396 | 31.51 | | 7.11 | 122.1 | |
| | 454 | 36.13 | | 6.81 | 117.1 | |
| Mixture 6 45/440 | 746 | 59.36 | 65.36 | 7.27 | 124.9 | 125.0 |
| | 824 | 65.57 | | 7.13 | 122.5 | |
| | 894 | 71.14 | | 7.42 | 127.5 | |
| Mixture 7 60/300 | 941 | 74.88 | 74.01 | 6.77 | 116.3 | 118.1 |
| | 1000 | 79.58 | | 6.78 | 116.6 | |
| | 849 | 67.56 | | 7.06 | 121.4 | |
| Mixture 8 60/370 | 1072 | 85.31 | 80.51 | 6.86 | 118.0 | 119.3 |
| | 996 | 79.26 | | 6.84 | 117.5 | |
| | 967 | 76.95 | | 7.13 | 122.5 | |
| 9 TTU CAP 60/440 | 1859 | 147.93 | 145.10 | 7.10 | 122.0 | 122.5 |
| | 2093 | 166.56 | | 7.08 | 121.7 | |
| | 1518 | 120.80 | | 7.19 | 123.7 | |
| Mixture 10 45/370 High Carbon Ash | 780 | 62.07 | 82.73 | 6.99 | 120.1 | 121.2 |
| | 1233 | 98.12 | | 7.06 | 121.4 | |
| | 1106 | 88.01 | | 7.11 | 122.1 | |

**Table A6. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| Mixture 11 60/370 High Carbon Ash | 1431 | 113.88 | 114.46 | 6.78 | 116.6 | 117.9 |
| | 1558 | 123.98 | | 6.79 | 116.6 | |
| | 1326 | 105.52 | | 7.00 | 120.4 | |
| Mixture 12 45/440 High Carbon Ash | 199 | 15.84 | 20.64 | 7.02 | 120.7 | 119.4 |
| | 208 | 16.55 | | 6.96 | 119.7 | |
| | 371 | 29.52 | | 6.86 | 117.8 | |
| Mixture 13 60/440 High Carbon Ash | 612 | 48.70 | 49.55 | 6.83 | 117.4 | 119.6 |
| | 509 | 40.50 | | 6.96 | 119.7 | |
| | 747 | 59.44 | | 7.09 | 121.8 | |
| Mixture 14 45/510 High Carbon Ash | 634 | 50.45 | 51.33 | 6.92 | 118.9 | 115.9 |
| | 563 | 44.80 | | 6.64 | 114.1 | |
| | 738 | 58.73 | | 6.67 | 114.6 | |
| Mixture 15 60/510 High Carbon Ash | 1442 | 114.75 | 117.14 | 7.12 | 122.4 | 120.1 |
| | 1526 | 121.44 | | 7.03 | 120.8 | |
| | 1448 | 115.23 | | 6.81 | 117.1 | |
| 16 Manufactured Limestone Sand 45/370 | 1087 | 86.50 | 83.08 | 7.31 | 125.6 | 123.6 |
| | 996 | 79.26 | | 7.19 | 123.5 | |
| | 1049 | 83.48 | | 7.09 | 121.8 | |
| 17 Crushed Sandstone Sand 45/370 | 1266 | 100.75 | 87.89 | 7.11 | 122.2 | 118.8 |
| | 943 | 75.04 | | 6.72 | 115.5 | |
| | 1057 | 84.11 | | 6.91 | 118.7 | |
| 18 Masonry Sand 45/370 | 1281 | 101.94 | 105.12 | 6.74 | 115.9 | 115.2 |
| | 1361 | 108.30 | | 6.59 | 113.2 | |
| | 1214 | 96.61 | | 6.78 | 116.5 | |
| 19 Limestone Screenings 45/370 | 1369 | 108.94 | 104.96 | 7.28 | 125.1 | 124.3 |
| | 1336 | 106.32 | | 7.16 | 123.1 | |
| | 1252 | 99.63 | | 7.26 | 124.8 | |

**Table A6. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 22 TDOT 100/250 | 2521 | 200.61 | 184.41 | 6.96 | 119.7 | 122.3 |
| | 2247 | 178.81 | | 7.45 | 128.0 | |
| | 2184 | 173.80 | | 6.94 | 119.3 | |
| 23 MBT MB AE 90 | 322 | 25.62 | 25.39 | 5.18 | 89.0 | 88.7 |
| | 237 | 18.86 | | 5.00 | 86.0 | |
| | 319 | 25.39 | | 5.31 | 91.2 | |
| 24 W.R. Grace Darafill | 967 | 76.95 | 72.92 | 5.71 | 98.1 | 98.2 |
| | 951 | 75.68 | | 5.68 | 97.7 | |
| | 831 | 66.13 | | 5.76 | 98.9 | |
| 25 MBT Rheofill Limestone Manufactured Sand | 406 | 32.31 | 25.65 | 5.29 | 90.9 | 93.2 |
| | 273 | 21.72 | | 5.52 | 94.9 | |
| | 288 | 22.92 | | 5.46 | 93.9 | |

**Table A7. 238-Day EFF Compressive Strength Data**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 1 KTC 30/300 | 106 | 8.44 | 8.59 | 6.69 | 115.0 | 113.8 |
| | 110 | 8.75 | | 6.55 | 112.6 | |
| | -- | -- | | -- | -- | |
| Mixture 2 30/370 | 173 | 13.77 | 13.13 | 6.93 | 119.2 | 118.3 |
| | 172 | 13.69 | | 6.91 | 118.8 | |
| | 150 | 11.94 | | 6.80 | 116.9 | |
| Mixture 3 30/440 | 225 | 17.90 | 20.37 | 6.61 | 113.7 | 116.0 |
| | 251 | 19.97 | | 6.49 | 111.6 | |
| | 292 | 23.24 | | 7.13 | 122.6 | |
| Mixture 4 45/300 | 470 | 37.40 | 42.73 | 6.90 | 118.5 | 118.7 |
| | 383 | 30.48 | | 6.90 | 118.7 | |
| | 758 | 60.32 | | 6.91 | 118.8 | |
| 5 TRMCA 45/370 | 475 | 37.80 | 38.70 | 6.88 | 118.2 | 118.3 |
| | 407 | 32.39 | | 6.84 | 117.6 | |
| | 577 | 45.92 | | 6.92 | 118.9 | |
| Mixture 6 45/440 | 643 | 51.17 | 61.14 | 7.14 | 122.7 | 122.5 |
| | 918 | 73.05 | | 7.13 | 122.6 | |
| | 744 | 59.21 | | 7.12 | 122.4 | |
| Mixture 7 60/300 | 1187 | 94.46 | 98.60 | 6.70 | 115.2 | 116.7 |
| | 1077 | 85.70 | | 6.85 | 117.8 | |
| | 1453 | 115.63 | | 6.82 | 117.2 | |
| Mixture 8 60/370 | 1033 | 82.20 | 85.86 | 6.79 | 116.6 | 117.0 |
| | 1090 | 86.74 | | 6.87 | 118.0 | |
| | 1114 | 88.65 | | 6.77 | 116.3 | |
| 9 TTU CAP 60/440 | 1400 | 111.41 | 125.89 | 6.88 | 118.2 | 119.6 |
| | 1795 | 142.84 | | 6.97 | 119.8 | |
| | 1551 | 123.42 | | 7.03 | 120.8 | |
| Mixture 10 45/370 High Carbon Ash | 800 | 63.66 | 74.56 | 6.72 | 115.6 | 115.8 |
| | 990 | 78.78 | | 6.66 | 114.5 | |
| | 1021 | 81.25 | | 6.83 | 117.4 | |

-- Sample did not survive de-molding

**Table A7. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| Mixture 11 60/370 High Carbon Ash | 1324 | 105.36 | 122.42 | 6.68 | 114.9 | 116.0 |
| | 1548 | 123.19 | | 6.77 | 116.4 | |
| | 1743 | 138.70 | | 6.79 | 116.7 | |
| Mixture 12 45/440 High Carbon Ash | 354 | 28.17 | 29.79 | 6.96 | 119.6 | 117.2 |
| | 421 | 33.50 | | 6.72 | 115.5 | |
| | 348 | 27.69 | | 6.78 | 116.6 | |
| Mixture 13 60/440 High Carbon Ash | 792 | 63.03 | 67.53 | 6.63 | 114.0 | 115.9 |
| | 918 | 73.05 | | 6.92 | 118.9 | |
| | 836 | 66.53 | | 6.68 | 114.9 | |
| Mixture 14 45/510 High Carbon Ash | 899 | 71.54 | 62.36 | 6.68 | 114.8 | 114.7 |
| | 687 | 54.67 | | 6.61 | 113.6 | |
| | 765 | 60.88 | | 6.73 | 115.7 | |
| Mixture 15 60/510 High Carbon Ash | 1638 | 130.35 | 127.19 | 6.86 | 117.9 | 116.0 |
| | 1642 | 130.67 | | 6.72 | 115.5 | |
| | 1515 | 120.56 | | 6.66 | 114.4 | |
| 16 Manufactured Limestone Sand 45/370 | 1142 | 90.88 | 96.71 | 7.14 | 122.7 | 119.7 |
| | 1309 | 104.17 | | 6.88 | 118.2 | |
| | 1195 | 95.10 | | 6.88 | 118.3 | |
| 17 Crushed Sandstone Sand 45/370 | 1329 | 105.76 | 118.17 | 6.58 | 113.2 | 115.3 |
| | 1641 | 130.59 | | 6.79 | 116.8 | |
| | 1488 | 118.41 | | 6.75 | 116.1 | |
| 18 Masonry Sand 45/370 | 1406 | 111.89 | 107.47 | 7.15 | 122.8 | 119.4 |
| | 1295 | 103.05 | | 7.08 | 121.6 | |
| | 1311 | 104.33 | | 6.62 | 113.7 | |
| 19 Limestone Screenings 45/370 | 1424 | 113.32 | 112.20 | 7.34 | 126.2 | 125.7 |
| | 1387 | 110.37 | | 7.20 | 123.8 | |
| | 1419 | 112.92 | | 7.39 | 127.1 | |

**Table A7. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 22 TDOT 100/250 | 2079 | 165.44 | 176.69 | 6.95 | 119.4 | 118.9 |
| | 2314 | 184.14 | | 6.85 | 117.7 | |
| | 2268 | 180.48 | | 6.96 | 119.6 | |
| 23 MBT MB AE 90 | 431 | 34.30 | 38.89 | 5.22 | 89.8 | 88.5 |
| | 550 | 43.77 | | 5.03 | 86.4 | |
| | 485 | 38.60 | | 5.19 | 89.2 | |
| 24 W.R. Grace Darafill | 1016 | 80.85 | 77.83 | 5.47 | 94.1 | 94.3 |
| | 940 | 74.80 | | 5.57 | 95.7 | |
| | 978 | 77.83 | | 5.41 | 93.0 | |
| 25 MBT Rheofill Limestone Manufactured Sand | 413 | 32.87 | 36.23 | 5.37 | 92.3 | 91.0 |
| | 541 | 43.05 | | 5.23 | 90.0 | |
| | 412 | 32.79 | | 5.28 | 90.8 | |

**Table A8. 301-Day EFF Compressive Strength Data**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 1 KTC 30/300 | 110 | 8.75 | 8.01 | 6.55 | 112.6 | 112.6 |
| | 72 | 5.73 | | 6.52 | 112.0 | |
| | 120 | 9.55 | | 6.59 | 113.2 | |
| Mixture 2 30/370 | 183 | 14.56 | 12.04 | 6.96 | 119.6 | 117.3 |
| | 101 | 8.04 | | 6.56 | 112.8 | |
| | 170 | 13.53 | | 6.95 | 119.5 | |
| Mixture 3 30/440 | 272 | 21.65 | 21.94 | 6.42 | 110.4 | 112.6 |
| | 262 | 20.85 | | 6.54 | 112.4 | |
| | 293 | 23.32 | | 6.69 | 114.9 | |
| Mixture 4 45/300 | 585 | 46.55 | 45.25 | 6.81 | 117.1 | 116.7 |
| | 500 | 39.79 | | 6.77 | 116.3 | |
| | 621 | 49.42 | | 6.78 | 116.5 | |
| 5 TRMCA 45/370 | 379 | 30.16 | 31.46 | 6.71 | 115.3 | 115.8 |
| | 459 | 36.53 | | 6.82 | 117.2 | |
| | 348 | 27.69 | | 6.69 | 115.0 | |
| Mixture 6 45/440 | 634 | 50.45 | 52.26 | 6.96 | 119.6 | 118.7 |
| | 588 | 46.79 | | 6.84 | 117.6 | |
| | 748 | 59.52 | | 6.92 | 118.9 | |
| Mixture 7 60/300 | 1204 | 95.81 | 78.86 | 6.62 | 113.8 | 113.7 |
| | 827 | 65.81 | | 6.58 | 113.1 | |
| | 942 | 74.96 | | 6.64 | 114.1 | |
| Mixture 8 60/370 | 1055 | 83.95 | 89.84 | 6.64 | 114.1 | 115.3 |
| | 1026 | 81.65 | | 6.74 | 115.9 | |
| | 1306 | 103.93 | | 6.74 | 115.9 | |
| 9 TTU CAP 60/440 | 1209 | 96.21 | 136.85 | 6.94 | 119.3 | 119.2 |
| | 1454 | 115.71 | | 6.90 | 118.6 | |
| | 2496 | 198.63 | | 6.96 | 119.6 | |
| Mixture 10 45/370 High Carbon Ash | 1036 | 82.44 | 86.58 | 6.68 | 114.8 | 115.4 |
| | 1336 | 106.32 | | 6.66 | 114.5 | |
| | 892 | 70.98 | | 6.80 | 116.9 | |

**Table A8. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| Mixture 11 60/370 High Carbon Ash | 1554 | 123.66 | 144.25 | 6.66 | 114.5 | 114.5 |
| | 1544 | 122.87 | | 6.62 | 113.8 | |
| | 2340 | 186.21 | | 6.70 | 115.2 | |
| Mixture 12 45/440 High Carbon Ash | 362 | 28.81 | 28.91 | 6.60 | 113.4 | 114.8 |
| | 317 | 25.23 | | 6.76 | 116.2 | |
| | 411 | 32.71 | | 6.68 | 114.8 | |
| Mixture 13 60/440 High Carbon Ash | 1194 | 95.02 | 83.18 | 6.60 | 113.4 | 113.2 |
| | 927 | 73.77 | | 6.58 | 113.1 | |
| | 1015 | 80.77 | | 6.58 | 113.1 | |
| Mixture 14 45/510 High Carbon Ash | 717 | 57.06 | 59.39 | 6.66 | 114.5 | 114.5 |
| | 721 | 57.38 | | 6.68 | 114.8 | |
| | 801 | 63.74 | | 6.64 | 114.1 | |
| Mixture 15 60/510 High Carbon Ash | 1457 | 115.94 | 131.91 | 6.62 | 113.8 | 113.6 |
| | 1915 | 152.39 | | 6.52 | 112.1 | |
| | 1601 | 127.40 | | 6.68 | 114.8 | |
| 16 Manufactured Limestone Sand 45/370 | 1141 | 90.80 | 87.93 | 6.80 | 116.9 | 120.8 |
| | 943 | 75.04 | | 7.28 | 125.1 | |
| | 1231 | 97.96 | | 7.00 | 120.3 | |
| 17 Crushed Sandstone Sand 45/370 | 1508 | 120.00 | 125.81 | 6.40 | 110.0 | 110.7 |
| | 1654 | 131.62 | | 6.48 | 111.4 | |
| | 1300 | 103.45 | | 6.44 | 110.7 | |
| 18 Masonry Sand 45/370 | 1351 | 107.51 | 107.95 | 6.62 | 113.8 | 112.2 |
| | 1362 | 108.38 | | 6.48 | 111.4 | |
| | 1655 | 131.70 | | 6.48 | 111.4 | |
| 19 Limestone Screenings 45/370 | 1396 | 111.09 | 116.85 | 6.98 | 120.0 | 118.6 |
| | 1624 | 129.23 | | 6.90 | 118.6 | |
| | 1385 | 110.21 | | 6.82 | 117.2 | |

**Table A8. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 22 TDOT 100/250 | 1711 | 136.16 | 168.25 | 6.94 | 119.3 | 117.8 |
| | 2482 | 197.51 | | 6.76 | 116.2 | |
| | 2150 | 171.09 | | 6.86 | 117.9 | |
| 23 MBT MB AE 90 | 431 | 34.30 | 37.59 | 4.94 | 84.9 | 85.7 |
| | 445 | 35.41 | | 4.88 | 83.9 | |
| | 541 | 43.05 | | 5.14 | 88.4 | |
| 24 W.R. Grace Darafill | 992 | 78.94 | 73.69 | 5.42 | 93.2 | 94.4 |
| | 889 | 70.74 | | 5.50 | 94.5 | |
| | 897 | 71.38 | | 5.56 | 95.6 | |
| 25 MBT Rheofill Limestone Manufactured Sand | 399 | 31.75 | 41.51 | 5.46 | 93.9 | 91.2 |
| | 561 | 44.64 | | 5.20 | 89.4 | |
| | 605 | 48.14 | | 5.26 | 90.4 | |

**Table A9. 364-Day EFF Compressive Strength Data**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 1 KTC 30/300 | 98 | 7.80 | 8.55 | 6.42 | 110.4 | 109.0 |
| | 117 | 9.31 | | 6.26 | 107.6 | |
| | -- | -- | | -- | -- | |
| Mixture 2 30/370 | 191 | 15.20 | 15.89 | 6.88 | 118.3 | 116.8 |
| | 184 | 14.64 | | 6.74 | 115.9 | |
| | 224 | 17.83 | | 6.76 | 116.2 | |
| Mixture 3 30/440 | 157 | 12.49 | 20.27 | 6.72 | 115.5 | 115.6 |
| | 310 | 24.67 | | 6.68 | 114.8 | |
| | 297 | 23.63 | | 6.78 | 116.5 | |
| Mixture 4 45/300 | 654 | 52.04 | 42.65 | 6.72 | 115.5 | 115.3 |
| | 445 | 35.41 | | 6.68 | 114.8 | |
| | 509 | 40.50 | | 6.72 | 115.5 | |
| 5 TRMCA 45/370 | 466 | 37.08 | 40.72 | 6.74 | 115.9 | 118.8 |
| | 468 | 37.24 | | 6.82 | 117.2 | |
| | 601 | 47.83 | | 7.18 | 123.4 | |
| Mixture 6 45/440 | 776 | 61.75 | 45.41 | 6.82 | 117.2 | 116.8 |
| | 517 | 41.14 | | 6.86 | 117.9 | |
| | 419 | 33.34 | | 6.70 | 115.2 | |
| Mixture 7 60/300 | 880 | 70.03 | 79.52 | 6.48 | 111.4 | 112.0 |
| | 1280 | 101.86 | | 6.52 | 112.1 | |
| | 838 | 66.69 | | 6.54 | 112.4 | |
| Mixture 8 60/370 | 1001 | 79.66 | 75.60 | 6.74 | 115.9 | 114.7 |
| | 961 | 76.47 | | 6.66 | 114.5 | |
| | 888 | 70.66 | | 6.62 | 113.8 | |
| 9 TTU CAP 60/440 | 1361 | 108.30 | 101.33 | 6.90 | 118.6 | 118.8 |
| | 1276 | 101.54 | | 6.94 | 119.3 | |
| | 1183 | 94.14 | | 6.90 | 118.6 | |
| Mixture 10 45/370 High Carbon Ash | 1481 | 117.85 | 74.22 | 6.66 | 114.5 | 112.2 |
| | 579 | 46.08 | | 6.38 | 109.7 | |
| | 738 | 58.73 | | 6.54 | 112.4 | |

-- Sample did not survive de-molding

**Table A9. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| Mixture 11 60/370 High Carbon Ash | 2090 | 166.32 | 138.68 | 6.74 | 115.9 | 115.5 |
| | 1267 | 100.82 | | 6.72 | 115.5 | |
| | 1871 | 148.89 | | 6.70 | 115.2 | |
| Mixture 12 45/440 High Carbon Ash | 383 | 30.48 | 28.33 | 6.62 | 113.8 | 113.8 |
| | 329 | 26.18 | | 6.62 | 113.8 | |
| | -- | -- | | -- | -- | |
| Mixture 13 60/440 High Carbon Ash | 917 | 72.97 | 62.63 | 6.86 | 117.9 | 115.4 |
| | 591 | 47.03 | | 6.66 | 114.5 | |
| | 853 | 67.88 | | 6.62 | 113.8 | |
| Mixture 14 45/510 High Carbon Ash | 972 | 77.35 | 67.93 | 6.58 | 113.1 | 113.3 |
| | 861 | 68.52 | | 6.52 | 112.1 | |
| | 728 | 57.93 | | 6.68 | 114.8 | |
| Mixture 15 60/510 High Carbon Ash | 1425 | 113.40 | 136.95 | 6.52 | 112.1 | 112.3 |
| | 1790 | 142.44 | | 6.50 | 111.7 | |
| | 1948 | 155.02 | | 6.58 | 113.1 | |
| 16 Manufactured Limestone Sand 45/370 | 1382 | 109.98 | 106.42 | 6.64 | 114.1 | 117.7 |
| | 1383 | 110.06 | | 6.72 | 115.5 | |
| | 1247 | 99.23 | | 7.18 | 123.4 | |
| 17 Crushed Sandstone Sand 45/370 | 1355 | 107.83 | 106.55 | 6.42 | 110.4 | 111.5 |
| | 1323 | 105.28 | | 6.34 | 109.0 | |
| | 1587 | 126.29 | | 6.70 | 115.2 | |
| 18 Masonry Sand 45/370 | 1376 | 109.50 | 110.33 | 6.54 | 112.4 | 110.9 |
| | 1397 | 111.17 | | 6.34 | 109.0 | |
| | 1402 | 111.57 | | 6.48 | 111.4 | |
| 19 Limestone Screenings 45/370 | 1779 | 141.57 | 133.66 | 6.86 | 117.9 | 117.6 |
| | 1647 | 131.06 | | 6.78 | 116.5 | |
| | 1613 | 128.36 | | 6.88 | 118.3 | |

-- Sample did not survive de-molding

**Table A9. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 22 TDOT 100/250 | 2550 | 202.92 | 201.36 | 6.94 | 119.3 | 118.3 |
| | 2730 | 217.25 | | 6.86 | 117.9 | |
| | 2311 | 183.90 | | 6.84 | 117.6 | |
| 23 MBT MB AE 90 | 418 | 33.26 | 35.15 | 4.90 | 84.2 | 84.9 |
| | 415 | 33.02 | | 5.00 | 85.9 | |
| | 492 | 39.15 | | 4.92 | 84.6 | |
| 24 W.R. Grace Darafill | 993 | 79.02 | 79.13 | 5.52 | 94.9 | 95.0 |
| | 971 | 77.27 | | 5.50 | 94.5 | |
| | 1019 | 81.09 | | 5.56 | 95.6 | |
| 25 MBT Rheofill Limestone Manufactured Sand | 504 | 40.11 | 43.74 | 5.14 | 88.4 | 89.0 |
| | 574 | 45.68 | | 5.26 | 90.4 | |
| | 571 | 45.44 | | 5.14 | 88.4 | |

**Table A10. 455-Day EFF Compressive Strength Data**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 1 KTC 30/300 | 90 | 7.16 | 7.80 | 6.30 | 108.3 | 110.2 |
| | 106 | 8.44 | | 6.52 | 112.1 | |
| | -- | -- | | -- | -- | |
| Mixture 2 30/370 | 168 | 13.37 | 13.74 | 6.82 | 117.2 | 117.6 |
| | 154 | 12.25 | | 6.80 | 116.9 | |
| | 196 | 15.60 | | 6.90 | 118.6 | |
| Mixture 3 30/440 | 242 | 19.26 | 19.89 | 6.60 | 113.4 | 113.8 |
| | 197 | 15.68 | | 6.80 | 116.9 | |
| | 311 | 24.75 | | 6.46 | 111.0 | |
| Mixture 4 45/300 | 503 | 40.03 | 42.20 | 6.66 | 114.5 | 115.1 |
| | 480 | 38.20 | | 6.72 | 115.5 | |
| | 608 | 48.38 | | 6.70 | 115.2 | |
| 5 TRMCA 45/370 | 330 | 26.26 | 27.27 | 6.62 | 113.8 | 114.2 |
| | 328 | 26.10 | | 6.64 | 114.1 | |
| | 370 | 29.44 | | 6.68 | 114.8 | |
| Mixture 6 45/440 | 652 | 51.88 | 55.55 | 6.82 | 117.2 | 116.2 |
| | 843 | 67.08 | | 6.68 | 114.8 | |
| | 599 | 47.67 | | 6.78 | 116.5 | |
| Mixture 7 60/300 | 748 | 59.52 | 59.26 | 6.56 | 112.8 | 111.8 |
| | 554 | 44.09 | | 6.40 | 110.0 | |
| | 932 | 74.17 | | 6.56 | 112.8 | |
| Mixture 8 60/370 | 878 | 69.87 | 70.72 | 6.70 | 115.2 | 114.4 |
| | 913 | 72.65 | | 6.60 | 113.4 | |
| | 875 | 69.63 | | 6.66 | 114.5 | |
| 9 TTU CAP 60/440 | 1495 | 118.97 | 129.39 | 6.88 | 118.3 | 118.5 |
| | 1584 | 126.05 | | 6.86 | 117.9 | |
| | 1799 | 143.16 | | 6.94 | 119.3 | |
| Mixture 10 45/370 High Carbon Ash | 1304 | 103.77 | 94.17 | 6.60 | 113.4 | 113.3 |
| | 1308 | 104.09 | | 6.56 | 112.8 | |
| | 938 | 74.64 | | 6.62 | 113.8 | |

-- Sample did not survive de-molding

**Table A10. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| Mixture 11 60/370 High Carbon Ash | 998 | 79.42 | 72.87 | 6.64 | 114.1 | 114.5 |
| | 718 | 57.14 | | 6.62 | 113.8 | |
| | 1031 | 82.04 | | 6.72 | 115.5 | |
| Mixture 12 45/440 High Carbon Ash | 301 | 23.95 | 29.55 | 6.58 | 113.1 | 113.8 |
| | 389 | 30.96 | | 6.62 | 113.8 | |
| | 424 | 33.74 | | 6.66 | 114.5 | |
| Mixture 13 60/440 High Carbon Ash | 1187 | 94.46 | 66.66 | 6.46 | 111.0 | 112.6 |
| | 465 | 37.00 | | 6.64 | 114.1 | |
| | 861 | 68.52 | | 6.56 | 112.8 | |
| Mixture 14 45/510 High Carbon Ash | 790 | 62.87 | 57.83 | 6.46 | 111.0 | 112.5 |
| | 569 | 45.28 | | 6.56 | 112.8 | |
| | 821 | 65.33 | | 6.62 | 113.8 | |
| Mixture 15 60/510 High Carbon Ash | 1590 | 126.53 | 123.29 | 6.48 | 111.4 | 111.6 |
| | 1673 | 133.13 | | 6.46 | 111.0 | |
| | 1385 | 110.21 | | 6.54 | 112.4 | |
| 16 Manufactured Limestone Sand 45/370 | 910 | 72.42 | 87.69 | 6.74 | 115.9 | 117.5 |
| | 1126 | 89.60 | | 7.14 | 122.7 | |
| | 1270 | 101.06 | | 6.62 | 113.8 | |
| 17 Crushed Sandstone Sand 45/370 | 1203 | 95.73 | 108.78 | 6.36 | 109.3 | 112.9 |
| | 1531 | 121.83 | | 6.52 | 112.1 | |
| | 1349 | 107.35 | | 6.82 | 117.2 | |
| 18 Masonry Sand 45/370 | 1469 | 116.90 | 105.64 | 6.52 | 112.1 | 110.9 |
| | 1186 | 94.38 | | 6.38 | 109.7 | |
| | 1257 | 100.03 | | 6.46 | 111.0 | |
| 19 Limestone Screenings 45/370 | 1613 | 128.36 | 120.59 | 6.94 | 119.3 | 118.3 |
| | 1526 | 121.44 | | 6.84 | 117.6 | |
| | 1407 | 111.97 | | 6.86 | 117.9 | |

**Table A10. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 22 TDOT 100/250 | 1937 | 154.14 | 170.11 | 6.66 | 114.5 | 116.1 |
| | 2192 | 174.43 | | 6.82 | 117.2 | |
| | 2284 | 181.75 | | 6.78 | 116.5 | |
| 23 MBT MB AE 90 | 598 | 47.59 | 34.54 | 5.04 | 86.6 | 86.1 |
| | 405 | 32.23 | | 4.98 | 85.6 | |
| | 299 | 23.79 | | 5.00 | 85.9 | |
| 24 W.R. Grace Darafill | 783 | 62.31 | 65.23 | 5.54 | 95.2 | 93.5 |
| | 903 | 71.86 | | 5.40 | 92.8 | |
| | 773 | 61.51 | | 5.38 | 92.5 | |
| 25 MBT Rheofill Limestone Manufactured Sand | 613 | 48.78 | 45.54 | 5.18 | 89.0 | 89.4 |
| | 538 | 42.81 | | 5.22 | 89.7 | |
| | 566 | 45.04 | | 5.20 | 89.4 | |

**Table A11. 546-Day EFF Compressive Strength Data**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 1 KTC 30/300 | 81 | 6.45 | 6.76 | 6.54 | 112.3 | 111.2 |
| | 66 | 5.25 | | 6.30 | 108.3 | |
| | 108 | 8.59 | | 6.58 | 113.0 | |
| Mixture 2 30/370 | 127 | 10.11 | 10.00 | 6.62 | 113.7 | 114.7 |
| | 125 | 9.95 | | 6.76 | 116.2 | |
| | 125 | 9.95 | | 6.64 | 114.1 | |
| Mixture 3 30/440 | 211 | 16.79 | 20.64 | 6.55 | 112.6 | 113.1 |
| | 277 | 22.04 | | 6.61 | 113.6 | |
| | 290 | 23.08 | | 6.58 | 113.1 | |
| Mixture 4 45/300 | 483 | 38.44 | 37.37 | 6.69 | 114.9 | 115.2 |
| | 395 | 31.43 | | 6.69 | 115.0 | |
| | 531 | 42.26 | | 6.73 | 115.8 | |
| 5 TRMCA 45/370 | 285 | 22.68 | 33.13 | 6.72 | 115.4 | 115.0 |
| | 444 | 35.33 | | 6.65 | 114.3 | |
| | 520 | 41.38 | | 6.71 | 115.3 | |
| Mixture 6 45/440 | 784 | 62.39 | 44.62 | 6.93 | 119.2 | 118.1 |
| | 470 | 37.40 | | 6.86 | 117.9 | |
| | 428 | 34.06 | | 6.82 | 117.2 | |
| Mixture 7 60/300 | 1081 | 86.02 | 66.05 | 6.57 | 112.9 | 112.8 |
| | 852 | 67.80 | | 6.60 | 113.4 | |
| | 557 | 44.32 | | 6.52 | 112.0 | |
| Mixture 8 60/370 | 1134 | 90.24 | 80.27 | 6.65 | 114.4 | 114.8 |
| | 863 | 68.68 | | 6.73 | 115.6 | |
| | 1029 | 81.89 | | 6.66 | 114.5 | |
| 9 TTU CAP 60/440 | 1372 | 109.18 | 89.23 | 6.83 | 117.5 | 119.1 |
| | 1109 | 88.25 | | 6.96 | 119.6 | |
| | 883 | 70.27 | | 7.00 | 120.3 | |
| Mixture 10 45/370 High Carbon Ash | 1115 | 88.73 | 79.31 | 6.63 | 113.9 | 114.1 |
| | 696 | 55.39 | | 6.64 | 114.1 | |
| | 1179 | 93.82 | | 6.65 | 114.3 | |

**Table A11. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| Mixture 11 60/370 High Carbon Ash | 859 | 68.36 | 90.61 | 6.71 | 115.3 | 114.8 |
| | 1290 | 102.65 | | 6.68 | 114.9 | |
| | 1267 | 100.82 | | 6.64 | 114.1 | |
| Mixture 12 45/440 High Carbon Ash | 278 | 22.12 | 23.08 | 6.64 | 114.1 | 114.0 |
| | 307 | 24.43 | | 6.60 | 113.4 | |
| | 285 | 22.68 | | 6.66 | 114.5 | |
| Mixture 13 60/440 High Carbon Ash | 794 | 63.18 | 58.86 | 6.62 | 113.9 | 114.5 |
| | 694 | 55.23 | | 6.65 | 114.3 | |
| | 731 | 58.17 | | 6.71 | 115.3 | |
| Mixture 14 45/510 High Carbon Ash | 770 | 61.27 | 59.50 | 6.58 | 113.1 | 113.2 |
| | 835 | 66.45 | | 6.59 | 113.3 | |
| | 638 | 50.77 | | 6.59 | 113.3 | |
| Mixture 15 60/510 High Carbon Ash | 1573 | 125.18 | 137.11 | 6.52 | 112.1 | 112.1 |
| | 1997 | 158.92 | | 6.49 | 111.5 | |
| | 1599 | 127.24 | | 6.56 | 112.8 | |
| 16 Manufactured Limestone Sand 45/370 | 1266 | 100.75 | 89.87 | 7.14 | 122.8 | 115.8 |
| | 970 | 77.19 | | 6.48 | 111.4 | |
| | 1152 | 91.67 | | 6.59 | 113.3 | |
| 17 Crushed Sandstone Sand 45/370 | 1234 | 98.20 | 120.04 | 6.44 | 110.6 | 110.4 |
| | 1783 | 141.89 | | 6.50 | 111.7 | |
| | 884 | 70.35 | | 6.34 | 109.0 | |
| 18 Masonry Sand 45/370 | 1095 | 87.14 | 96.21 | 6.33 | 108.7 | 109.9 |
| | 1323 | 105.28 | | 6.31 | 108.5 | |
| | 1825 | 145.23 | | 6.55 | 112.5 | |
| 19 Limestone Screenings 45/370 | 1815 | 144.43 | 126.69 | 6.85 | 117.7 | 117.3 |
| | 1483 | 118.01 | | 6.86 | 117.9 | |
| | 1478 | 117.62 | | 6.77 | 116.4 | |

**Table A11. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 22 TDOT 100/250 | 2838 | 225.84 | 195.55 | 6.73 | 115.8 | 116.0 |
| | 1894 | 150.72 | | 6.75 | 116.0 | |
| | 2640 | 210.08 | | 6.77 | 116.3 | |
| 23 MBT MB AE 90 | 429 | 34.14 | 30.11 | 5.01 | 86.2 | 84.9 |
| | 340 | 27.06 | | 4.92 | 84.6 | |
| | 366 | 29.13 | | 4.88 | 83.9 | |
| 24 W.R. Grace Darafill | 881 | 70.11 | 60.96 | 5.51 | 94.6 | 94.9 |
| | 762 | 60.64 | | 5.49 | 94.3 | |
| | 655 | 52.12 | | 5.57 | 95.7 | |
| 25 MBT Rheofill Limestone Manufactured Sand | 547 | 43.53 | 40.80 | 5.23 | 89.8 | 89.4 |
| | 531 | 42.26 | | 5.23 | 89.9 | |
| | 460 | 36.61 | | 5.14 | 88.3 | |

## Table A12. 637-Day EFF Compressive Strength Data

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 1 KTC 30/300 | 98 | 7.80 | 7.80 | 6.42 | 110.4 | 110.4 |
| | -- | -- | | -- | -- | |
| | -- | -- | | -- | -- | |
| Mixture 2 30/370 | 213 | 16.95 | 15.20 | 6.78 | 116.5 | 115.8 |
| | 193 | 15.36 | | 6.71 | 115.4 | |
| | 167 | 13.29 | | 6.73 | 115.6 | |
| Mixture 3 30/440 | 174 | 13.85 | 16.95 | 6.57 | 112.9 | 112.6 |
| | 287 | 22.84 | | 6.62 | 113.7 | |
| | 178 | 14.16 | | 6.47 | 111.1 | |
| Mixture 4 45/300 | 418 | 33.26 | 47.80 | 6.73 | 115.7 | 116.4 |
| | 699 | 55.62 | | 6.80 | 116.8 | |
| | 685 | 54.51 | | 6.79 | 116.8 | |
| 5 TRMCA 45/370 | 316 | 25.15 | 32.63 | 6.71 | 115.4 | 115.1 |
| | 483 | 38.44 | | 6.73 | 115.6 | |
| | 431 | 34.30 | | 6.64 | 114.2 | |
| Mixture 6 45/440 | 793 | 63.10 | 67.77 | 6.84 | 117.5 | 117.5 |
| | 648 | 51.57 | | 6.83 | 117.4 | |
| | 1114 | 88.65 | | 6.84 | 117.6 | |
| Mixture 7 60/300 | 522 | 41.54 | 47.61 | 6.33 | 108.8 | 109.6 |
| | 543 | 43.21 | | 6.52 | 112.0 | |
| | 730 | 58.09 | | 6.29 | 108.0 | |
| Mixture 8 60/370 | 1005 | 79.98 | 66.00 | 6.75 | 116.0 | 115.6 |
| | 803 | 63.90 | | 6.72 | 115.6 | |
| | 680 | 54.11 | | 6.71 | 115.3 | |
| 9 TTU CAP 60/440 | 1387 | 110.37 | 107.54 | 6.95 | 119.4 | 119.6 |
| | 1355 | 107.83 | | 6.99 | 120.2 | |
| | 1312 | 104.41 | | 6.95 | 119.4 | |
| Mixture 10 45/370 High Carbon Ash | 703 | 55.94 | 55.12 | 6.45 | 110.9 | 110.7 |
| | 585 | 46.55 | | 6.45 | 110.8 | |
| | 790 | 62.87 | | 6.42 | 110.4 | |

-- Sample did not survive de-molding

**Table A12. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| Mixture 11 60/370 High Carbon Ash | 1620 | 128.92 | 100.96 | 6.59 | 113.3 | 113.7 |
| | 1264 | 100.59 | | 6.63 | 113.9 | |
| | 922 | 73.37 | | 6.63 | 114.0 | |
| Mixture 12 45/440 High Carbon Ash | 351 | 27.93 | 24.22 | 6.66 | 114.4 | 113.5 |
| | 333 | 26.50 | | 6.60 | 113.4 | |
| | 229 | 18.22 | | 6.55 | 112.6 | |
| Mixture 13 60/440 High Carbon Ash | 822 | 65.41 | 53.50 | 6.60 | 113.4 | 113.4 |
| | 603 | 47.99 | | 6.54 | 112.3 | |
| | 592 | 47.11 | | 6.66 | 114.5 | |
| Mixture 14 45/510 High Carbon Ash | 809 | 64.38 | 58.04 | 6.78 | 116.6 | 116.7 |
| | 714 | 56.82 | | 6.81 | 117.0 | |
| | 665 | 52.92 | | 6.78 | 116.6 | |
| Mixture 15 60/510 High Carbon Ash | 1187 | 94.46 | 98.36 | 6.50 | 111.7 | 112.3 |
| | 1383 | 110.06 | | 6.48 | 111.4 | |
| | 1138 | 90.56 | | 6.61 | 113.6 | |
| 16 Manufactured Limestone Sand 45/370 | 947 | 75.36 | 76.16 | 6.51 | 111.9 | 113.0 |
| | 981 | 78.07 | | 6.56 | 112.8 | |
| | 943 | 75.04 | | 6.64 | 114.2 | |
| 17 Crushed Sandstone Sand 45/370 | 1166 | 92.79 | 94.22 | 6.39 | 109.9 | 109.6 |
| | 1202 | 95.65 | | 6.36 | 109.3 | |
| | 1118 | 88.97 | | 6.37 | 109.6 | |
| 18 Masonry Sand 45/370 | 937 | 74.56 | 83.04 | 6.21 | 106.7 | 108.2 |
| | 1150 | 91.51 | | 6.37 | 109.6 | |
| | 976 | 77.67 | | 6.30 | 108.3 | |
| 19 Limestone Screenings 45/370 | 1337 | 106.40 | 119.07 | 6.87 | 118.1 | 117.2 |
| | 1549 | 123.27 | | 6.83 | 117.4 | |
| | 1603 | 127.56 | | 6.76 | 116.1 | |

**Table A12. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 22 TDOT 100/250 | 1844 | 146.74 | 149.79 | 6.63 | 113.9 | 114.6 |
| | 1853 | 147.46 | | 6.65 | 114.3 | |
| | 1950 | 155.18 | | 6.73 | 115.6 | |
| 23 MBT MB AE 90 | 371 | 29.52 | 29.05 | 4.99 | 85.8 | 85.0 |
| | 358 | 28.49 | | 4.92 | 84.6 | |
| | 366 | 29.13 | | 4.93 | 84.7 | |
| 24 W.R. Grace Darafill | 778 | 61.91 | 54.86 | 5.50 | 94.5 | 94.0 |
| | 670 | 53.32 | | 5.37 | 92.4 | |
| | 620 | 49.34 | | 5.53 | 95.1 | |
| 25 MBT Rheofill Limestone Manufactured Sand | -- | -- | -- | -- | -- | -- |
| | -- | -- | | -- | -- | |
| | -- | -- | | -- | -- | |

-- Sample did not survive de-molding

**Table A13. 637-Day EFF Lime Water Immersed Compressive Strength Data**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 1 KTC 30/300 | -- | -- | -- | -- | -- | -- |
| | -- | -- | | -- | -- | |
| | -- | -- | | -- | -- | |
| Mixture 2 30/370 | 111 | 8.83 | 10.46 | 7.13 | 122.6 | 123.7 |
| | 152 | 12.10 | | 7.26 | 124.7 | |
| | -- | -- | | -- | -- | |
| Mixture 3 30/440 | 155 | 12.33 | 12.81 | 7.15 | 122.9 | 122.6 |
| | 167 | 13.29 | | 7.11 | 122.3 | |
| | -- | -- | | -- | -- | |
| Mixture 4 45/300 | 516 | 41.06 | 42.26 | 7.66 | 131.7 | 131.9 |
| | 426 | 33.90 | | 7.64 | 131.4 | |
| | 651 | 51.80 | | 7.71 | 132.5 | |
| 5 TRMCA 45/370 | 359 | 28.57 | 24.01 | 7.52 | 129.2 | 128.8 |
| | 265 | 21.09 | | 7.46 | 128.2 | |
| | 281 | 22.36 | | 7.50 | 128.9 | |
| Mixture 6 45/440 | 609 | 48.46 | 49.28 | 7.62 | 130.9 | 131.2 |
| | 562 | 44.72 | | 7.64 | 131.3 | |
| | 687 | 54.67 | | 7.66 | 131.6 | |
| Mixture 7 60/300 | 588 | 46.79 | 45.28 | 7.39 | 127.1 | 127.8 |
| | 531 | 42.26 | | 7.50 | 129.0 | |
| | 588 | 46.79 | | 7.40 | 127.3 | |
| Mixture 8 60/370 | 733 | 58.33 | 57.32 | 7.63 | 131.1 | 131.7 |
| | 682 | 54.27 | | 7.70 | 132.3 | |
| | 746 | 59.36 | | 7.67 | 131.8 | |
| 9 TTU CAP 60/440 | 1607 | 127.88 | 127.68 | 7.68 | 132.1 | 132.0 |
| | 1602 | 127.48 | | 7.67 | 131.9 | |
| | 0 | 0.00 | | 0.00 | 0.0 | |
| Mixture 10 45/370 High Carbon Ash | 1573 | 125.18 | 84.31 | 7.54 | 129.6 | 129.6 |
| | 546 | 43.45 | | 7.53 | 129.5 | |
| | 0 | 0.00 | | 0.00 | 0.0 | |

-- Sample did not survive Lime Water Immersion

**Table A13. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| Mixture 11 60/370 High Carbon Ash | 819 | 65.17 | 85.23 | 7.43 | 127.6 | 129.6 |
| | 1268 | 100.90 | | 7.66 | 131.6 | |
| | 1126 | 89.60 | | 7.54 | 129.6 | |
| Mixture 12 45/440 High Carbon Ash | 342 | 27.22 | 26.30 | 7.57 | 130.0 | 128.3 |
| | 319 | 25.39 | | 7.36 | 126.5 | |
| | -- | -- | | -- | -- | |
| Mixture 13 60/440 High Carbon Ash | 762 | 60.64 | 63.48 | 7.56 | 129.9 | 129.9 |
| | 846 | 67.32 | | 7.55 | 129.7 | |
| | 785 | 62.47 | | 7.56 | 130.0 | |
| Mixture 14 45/510 High Carbon Ash | 760 | 60.48 | 53.00 | 7.68 | 132.0 | 130.7 |
| | 543 | 43.21 | | 7.60 | 130.7 | |
| | 695 | 55.31 | | 7.52 | 129.3 | |
| Mixture 15 60/510 High Carbon Ash | 1519 | 120.88 | 131.73 | 7.43 | 127.7 | 127.4 |
| | 1619 | 128.84 | | 7.41 | 127.4 | |
| | 1828 | 145.47 | | 7.39 | 127.0 | |
| 16 Manufactured Limestone Sand 45/370 | 741 | 58.97 | 65.65 | 7.44 | 127.9 | 129.8 |
| | 801 | 63.74 | | 7.66 | 131.6 | |
| | 933 | 74.25 | | 7.56 | 129.9 | |
| 17 Crushed Sandstone Sand 45/370 | 1129 | 89.84 | 83.76 | 7.23 | 124.2 | 125.3 |
| | 976 | 77.67 | | 7.34 | 126.1 | |
| | 957 | 76.16 | | 7.30 | 125.5 | |
| 18 Masonry Sand 45/370 | 1468 | 116.82 | 103.73 | 7.36 | 126.5 | 125.9 |
| | 1139 | 90.64 | | 7.28 | 125.1 | |
| | 1526 | 121.44 | | 7.34 | 126.2 | |
| 19 Limestone Screenings 45/370 | 1520 | 120.96 | 114.96 | 7.78 | 133.8 | 133.6 |
| | 1481 | 117.85 | | 7.72 | 132.6 | |
| | 1333 | 106.08 | | 7.82 | 134.3 | |

-- Sample did not survive Lime Water Immersion

**Table A13. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 22 TDOT 100/250 | 1716 | 136.55 | 158.68 | 7.57 | 130.0 | 129.5 |
| | 2446 | 194.65 | | 7.45 | 128.1 | |
| | 1820 | 144.83 | | 7.59 | 130.4 | |
| 23 MBT MB AE 90 | 253 | 20.13 | 26.23 | 6.03 | 103.7 | 103.2 |
| | 407 | 32.39 | | 5.94 | 102.0 | |
| | 329 | 26.18 | | 6.04 | 103.8 | |
| 24 W.R. Grace Darafill | 618 | 49.18 | 48.28 | 6.52 | 112.0 | 111.7 |
| | 654 | 52.04 | | 6.47 | 111.2 | |
| | 548 | 43.61 | | 6.51 | 111.9 | |
| 25 MBT Rheofill Limestone Manufactured Sand | 230 | 18.30 | 19.44 | 6.29 | 108.2 | 109.1 |
| | 282 | 22.44 | | 6.43 | 110.6 | |
| | 221 | 17.59 | | 6.31 | 108.5 | |

**Table A14. 728-Day EFF Compressive Strength Data**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 1 KTC 30/300 | -- | -- | -- | -- | -- | -- |
| | -- | -- | | -- | -- | |
| | -- | -- | | -- | -- | |
| Mixture 2 30/370 | 111 | 8.83 | 10.46 | 7.13 | 122.6 | 123.7 |
| | 152 | 12.10 | | 7.26 | 124.7 | |
| | -- | -- | | -- | -- | |
| Mixture 3 30/440 | 155 | 12.33 | 12.81 | 7.15 | 122.9 | 122.6 |
| | 167 | 13.29 | | 7.11 | 122.3 | |
| | -- | -- | | -- | -- | |
| Mixture 4 45/300 | 516 | 41.06 | 42.26 | 7.66 | 131.7 | 131.9 |
| | 426 | 33.90 | | 7.64 | 131.4 | |
| | 651 | 51.80 | | 7.71 | 132.5 | |
| 5 TRMCA 45/370 | 359 | 28.57 | 24.01 | 7.52 | 129.2 | 128.8 |
| | 265 | 21.09 | | 7.46 | 128.2 | |
| | 281 | 22.36 | | 7.50 | 128.9 | |
| Mixture 6 45/440 | 636 | 50.61 | 55.7 | 6.81 | 117.1 | 116.6 |
| | 604 | 48.06 | | 6.68 | 114.8 | |
| | 859 | 68.36 | | 6.86 | 117.9 | |
| Mixture 7 60/300 | 588 | 46.79 | 52.8 | 6.42 | 110.4 | 111.27 |
| | 790 | 62.87 | | 6.46 | 111.0 | |
| | 614 | 48.86 | | 6.54 | 112.4 | |
| Mixture 8 60/370 | 1090 | 86.74 | 79.3 | 6.68 | 114.8 | 114.71 |
| | 945 | 75.20 | | 6.68 | 114.8 | |
| | 953 | 75.84 | | 6.66 | 114.5 | |
| 9 TTU CAP 60/440 | 1561 | 124.22 | 107.7 | 6.76 | 116.2 | 117.00 |
| | 1351 | 107.51 | | 6.84 | 117.6 | |
| | 1149 | 91.43 | | 6.82 | 117.2 | |
| Mixture 10 45/370 High Carbon Ash | 1131 | 90.00 | 71.2 | 6.52 | 112.1 | 111.15 |
| | 624 | 73.53 | | 6.34 | 109.0 | |
| | 631 | 50.21 | | 6.54 | 112.4 | |

-- Sample did not survive de-molding

**Table A14. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| Mixture 11 60/370 High Carbon Ash | 2075 | 165.12 | 110.5 | 6.56 | 112.8 | 113.10 |
| | 1024 | 81.49 | | 6.60 | 113.4 | |
| | 1067 | 84.91 | | 6.58 | 113.1 | |
| Mixture 12 45/440 High Carbon Ash | 209 | 16.63 | 15.9 | 6.52 | 112.1 | 112.60 |
| | 190 | 15.12 | | 6.58 | 113.1 | |
| | -- | -- | | -- | -- | |
| Mixture 13 60/440 High Carbon Ash | 792 | 63.03 | 66.3 | 6.60 | 113.4 | 112.87 |
| | 839 | 66.77 | | 6.52 | 112.1 | |
| | 868 | 69.07 | | 6.58 | 113.1 | |
| Mixture 14 45/510 High Carbon Ash | 758 | 60.32 | 58.7 | 6.68 | 114.8 | 115.05 |
| | 801 | 63.74 | | 6.66 | 114.5 | |
| | 653 | 51.96 | | 6.74 | 115.9 | |
| Mixture 15 60/510 High Carbon Ash | 1868 | 132.74 | 126.6 | 6.52 | 112.1 | 112.07 |
| | 1754 | 139.58 | | 6.46 | 111.0 | |
| | 1350 | 107.43 | | 6.58 | 113.1 | |
| 16 Manufactured Limestone Sand 45/370 | 836 | 66.53 | 73.7 | 6.46 | 111.0 | 112.07 |
| | 721 | 57.38 | | 6.46 | 111.0 | |
| | 1220 | 97.08 | | 6.64 | 114.1 | |
| 17 Crushed Sandstone Sand 45/370 | 1114 | 88.65 | 85.0 | 6.34 | 109.0 | 108.63 |
| | 1022 | 81.33 | | 6.30 | 108.3 | |
| | 1152 | 91.67 | | 6.32 | 108.6 | |
| 18 Masonry Sand 45/370 | 1944 | 154.70 | 127.6 | 6.44 | 110.7 | 109.67 |
| | 1263 | 100.51 | | 6.28 | 107.9 | |
| | 1745 | 138.86 | | 6.42 | 110.4 | |
| 19 Limestone Screenings 45/370 | 1477 | 117.54 | 111.0 | 6.68 | 114.8 | 114.82 |
| | 1162 | 92.47 | | 6.68 | 114.8 | |
| | 1544 | 122.87 | | 6.68 | 114.8 | |

-- Sample did not survive de-molding

**Table A14. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 22 TDOT 100/250 | 2576 | 204.99 | 198.0 | 6.78 | 116.5 | 116.31 |
| | 2936 | 233.64 | | 6.84 | 117.6 | |
| | 1953 | 155.41 | | 6.68 | 114.8 | |
| 23 MBT MB AE 90 | 338 | 26.90 | 25.6 | 4.94 | 84.9 | 84.45 |
| | 357 | 28.41 | | 4.90 | 84.2 | |
| | 271 | 21.57 | | 4.90 | 84.2 | |
| 24 W.R. Grace Darafill | 688 | 54.75 | 53.2 | 5.32 | 91.4 | 93.28 |
| | 518 | 41.22 | | 5.50 | 94.5 | |
| | 799 | 63.58 | | 5.46 | 93.9 | |
| 25 MBT Rheofill Limestone Manufactured Sand | 380 | 30.24 | 39.4 | 5.14 | 88.4 | 87.78 |
| | 514 | 40.90 | | 5.12 | 88.0 | |
| | 591 | 47.03 | | 5.06 | 87.0 | |

**Table A15. 728-Day EFF Lime Water Immersed Compressive Strength Data**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 1 KTC 30/300 | -- | -- | -- | -- | -- | -- |
| | -- | -- | | -- | -- | |
| | -- | -- | | -- | -- | |
| Mixture 2 30/370 | -- | -- | -- | -- | -- | -- |
| | -- | -- | | -- | -- | |
| | -- | -- | | -- | -- | |
| Mixture 3 30/440 | 201 | 16.00 | 16.7 | 7.18 | 123.4 | 124.1 |
| | 218 | 17.35 | | 7.26 | 124.8 | |
| | -- | -- | | --- | -- | |
| Mixture 4 45/300 | 421 | 33.50 | 33.5 | 7.64 | 131.3 | 131.3 |
| | -- | -- | | -- | -- | |
| | -- | -- | | -- | -- | |
| 5 TRMCA 45/370 | 359 | 28.57 | 22.2 | 7.56 | 129.9 | 126.3 |
| | 200 | 15.92 | | 7.14 | 122.7 | |
| | | | | | | |
| Mixture 6 45/440 | 655 | 52.12 | 47.1 | 7.66 | 131.7 | 130.75 |
| | 531 | 42.26 | | 7.52 | 129.3 | |
| | 589 | 46.87 | | 7.64 | 131.3 | |
| Mixture 7 60/300 | 668 | 53.16 | 48.3 | 7.44 | 127.9 | 127.31 |
| | 486 | 38.67 | | 7.36 | 126.5 | |
| | 668 | 53.16 | | 7.42 | 127.5 | |
| Mixture 8 60/370 | 853 | 67.88 | 68.8 | 7.60 | 130.6 | 130.75 |
| | 893 | 71.06 | | 7.64 | 131.3 | |
| | 846 | 67.32 | | 7.58 | 130.3 | |
| 9 TTU CAP 60/440 | 1600 | 127.32 | 116.3 | 7.70 | 132.4 | 132.13 |
| | 1491 | 118.65 | | 7.70 | 132.4 | |
| | 1293 | 102.89 | | 7.66 | 131.7 | |
| Mixture 10 45/370 High Carbon Ash | 693 | 55.15 | 55.15 | 7.46 | 126.2 | 126.2 |
| | -- | -- | | -- | -- | |
| | -- | -- | | -- | -- | |

-- Sample did not survive Lime Water Immersion

**Table A15. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| Mixture 11 60/370 High Carbon Ash | 1135 | 90.32 | 100.4 | 7.46 | 128.2 | 128.80 |
| | 1333 | 106.08 | | 7.54 | 129.6 | |
| | 1317 | 104.80 | | 7.48 | 128.6 | |
| Mixture 12 45/440 High Carbon Ash | 360 | 28.65 | 29.2 | 7.50 | 128.9 | 128.92 |
| | 356 | 28.33 | | 7.50 | 128.9 | |
| | 384 | 30.56 | | 7.50 | 128.9 | |
| Mixture 13 60/440 High Carbon Ash | 914 | 72.73 | 68.1 | 7.50 | 128.9 | 129.10 |
| | 798 | 63.50 | | 7.52 | 129.3 | |
| | -- | -- | | -- | -- | |
| Mixture 14 45/510 High Carbon Ash | 643 | 51.17 | 51.2 | 7.54 | 129.6 | 129.6 |
| | -- | -- | | -- | -- | |
| | -- | -- | | -- | -- | |
| Mixture 15 60/510 High Carbon Ash | 1336 | 106.32 | 100.9 | 7.60 | 130.6 | 128.00 |
| | 1010 | 80.37 | | 7.34 | 126.2 | |
| | 1459 | 116.10 | | 7.40 | 127.2 | |
| 16 Manufactured Limestone Sand 45/370 | 951 | 75.68 | 75.7 | 7.58 | 129.9 | 129.9 |
| | -- | -- | | -- | -- | |
| | -- | -- | | -- | -- | |
| 17 Crushed Sandstone Sand 45/370 | 1268 | 100.90 | 93.8 | 7.30 | 125.5 | 125.25 |
| | 1089 | 86.66 | | 7.26 | 124.8 | |
| | 959 | 76.31 | | 7.30 | 125.5 | |
| 18 Masonry Sand 45/370 | 1599 | 127.24 | 116.0 | 7.26 | 124.8 | 124.80 |
| | 1317 | 104.80 | | 7.26 | 124.8 | |
| | -- | -- | | -- | -- | |
| 19 Limestone Screenings 45/370 | 1449 | 115.31 | 107.1 | 7.74 | 133.0 | 132.81 |
| | 1392 | 110.77 | | 7.74 | 133.0 | |
| | 1195 | 95.10 | | 7.70 | 132.4 | |

-- Sample did not survive Lime Water Immersion

**Table A15. (Continued)**

| Mixture | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 22 TDOT 100/250 | 2006 | 159.63 | 150.3 | 7.48 | 128.6 | 128.11 |
| | 1957 | 155.73 | | 7.44 | 127.9 | |
| | 1705 | 135.68 | | 7.44 | 127.9 | |
| 23 MBT MB AE 90 | 163 | 12.97 | 15.1 | 6.12 | 105.2 | 104.28 |
| | 115 | 9.15 | | 6.04 | 103.8 | |
| | 291 | 23.16 | | 6.04 | 103.8 | |
| 24 W.R. Grace Darafill | 618 | 49.18 | 45.8 | 6.56 | 112.8 | 111.27 |
| | 508 | 40.43 | | 6.42 | 110.4 | |
| | 602 | 47.91 | | 6.44 | 110.7 | |
| 25 MBT Rheofill Limestone Manufactured Sand | 187 | 14.88 | 15.2 | 6.42 | 110.4 | 109.89 |
| | 175 | 13.93 | | 6.36 | 109.3 | |
| | 212 | 16.87 | | 6.40 | 110.0 | |

# APPENDIX B

**Table B1. Algood, TN ZOOM! CLSM Demo – Limestone Screenings Cylinders 09/23/02**

| Age (days) | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 1 | 2159 | 171.76 | 168.42 | 6.26 | 107.60 | 106.80 |
| | 2068 | 164.52 | | 6.18 | 106.23 | |
| | 2124 | 168.97 | | 6.20 | 106.57 | |
| 7 | 4555 | 362.37 | 355.87 | 6.22 | 106.91 | 106.91 |
| | 4358 | 346.70 | | 6.18 | 106.23 | |
| | 4507 | 358.55 | | 6.26 | 107.60 | |
| 28 | 6218 | 494.67 | 512.57 | 6.12 | 105.19 | 105.77 |
| | 5988 | 476.37 | | 6.18 | 106.23 | |
| | 7123 | 566.67 | | 6.16 | 105.88 | |
| 56 | 7063 | 561.89 | 616.65 | 6.06 | 104.16 | 104.85 |
| | 7648 | 608.43 | | 6.14 | 105.54 | |
| | 8543 | 679.63 | | 6.10 | 104.85 | |

**Table B2. Algood, TN ZOOM! CLSM Demo – Ohio River Sand Cylinders 09/23/02**

| Age (days) | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 1 | 1325 | 105.41 | 96.31 | 6.24 | 107.26 | 107.83 |
| | 1234 | 98.17 | | 6.30 | 108.29 | |
| | 1073 | 85.36 | | 6.28 | 107.94 | |
| 7 | 2804 | 223.07 | 225.06 | 6.22 | 106.91 | 107.60 |
| | 2885 | 229.51 | | 6.30 | 108.29 | |
| | 2798 | 222.59 | | 6.26 | 107.60 | |
| 28 | 4490 | 357.20 | 328.88 | 6.16 | 105.88 | 106.34 |
| | 4292 | 341.45 | | 6.20 | 106.57 | |
| | 3620 | 287.99 | | 6.20 | 106.57 | |
| 56 | 5532 | 440.10 | 431.56 | 6.18 | 106.23 | 105.42 |
| | 4612 | 366.91 | | 6.04 | 103.82 | |
| | 6130 | 487.67 | | 6.18 | 6.18 | |

**Table B3. Knoxville, TN ZOOM! CLSM Demo – Manufactured Limestone Sand Cylinders, 11/01/02 (Trench #1)**

| Age (days) | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 1 | 1762 | 140.18 | 142.75 | 7.38 | 126.85 | 127.31 |
| | 1791 | 142.48 | | 7.16 | 123.07 | |
| | 1830 | 145.58 | | 7.68 | 127.31 | |
| 7 | 3829 | 304.61 | 312.81 | 7.50 | 128.91 | 128.34 |
| | 4081 | 324.66 | | 7.44 | 127.88 | |
| | 3886 | 309.15 | | 7.46 | 128.26 | |
| 28 | 5602 | 445.66 | 448.13 | 7.42 | 127.54 | 127.65 |
| | 2849 | 465.31 | | 7.50 | 128.91 | |
| | 5448 | 433.41 | | 7.36 | 126.51 | |
| 56 | 5832 | 463.96 | 491.38 | 7.22 | 124.10 | 123.53 |
| | 6567 | 522.43 | | 7.22 | 124.10 | |
| | 6131 | 487.75 | | 7.12 | 122.38 | |

**Table B4. Knoxville, TN ZOOM! CLSM Demo – Manufactured Limestone Sand Cylinders, 11/01/02 (Trench #2)**

| Age (days) | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 1 | 1449 | 115.27 | 96.50 | 6.14 | 105.54 | 103.13 |
| | 1023 | 81.38 | | 5.92 | 101.76 | |
| | 1167 | 92.84 | | 5.94 | 102.10 | |
| 7 | 3153 | 250.84 | 249.43 | 5.96 | 102.44 | 102.22 |
| | 2925 | 232.70 | | 5.94 | 102.10 | |
| | 3328 | 264.76 | | 5.94 | 102.10 | |
| 28 | 4838 | 384.88 | 370.91 | N/A | N/A | N/A |
| | 4731 | 376.37 | | N/A | N/A | |
| | 4418 | 351.47 | | N/A | N/A | |
| 56 | 5511 | 438.42 | 426.33 | 5.78 | 99.35 | 101.76 |
| | 5434 | 432.30 | | 6.02 | 103.48 | |
| | 5132 | 408.24 | | 5.96 | 102.44 | |

**Table B5. Nashville, TN ZOOM! CLSM Demo – Ohio River Sand Cylinders, 11/08/02 (Trench #1)**

| Age (days) | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 1 | 1317 | 104.77 | 101.59 | 5.92 | 101.76 | 100.95 |
| | 1260 | 100.24 | | 5.82 | 100.04 | |
| | 1254 | 99.76 | | 5.88 | 101.07 | |
| 7 | 3132 | 249.16 | 231.87 | 5.82 | 100.04 | 100.38 |
| | 2695 | 214.40 | | 5.84 | 100.38 | |
| | 2917 | 232.60 | | 5.86 | 100.73 | |
| 28 | 4477 | 356.17 | 323.97 | 5.76 | 99.01 | 99.01 |
| | 3494 | 277.96 | | 5.72 | 98.32 | |
| | 4246 | 337.79 | | 5.80 | 99.69 | |
| 56 | 5076 | 403.82 | 381.09 | 5.72 | 98.35 | 98.67 |
| | 4598 | 365.79 | | 5.83 | 100.12 | |
| | 4697 | 373.67 | | 5.68 | 97.55 | |

**Table B6. Nashville, TN ZOOM CLSM Demo – Ohio River Sand Cylinders, 11/08/02 (Trench #2)**

| Age (days) | Compressive Strength | | | Unit Weight | | |
|---|---|---|---|---|---|---|
| | Load (lbs) | Individual (psi) | Average (psi) | Weight (lbs) | Individual (pcf) | Average (pcf) |
| 1 | 1278 | 101.67 | 103.77 | 5.84 | 100.38 | 100.27 |
| | 1306 | 103.90 | | 5.84 | 100.38 | |
| | 1329 | 105.73 | | 5.82 | 100.04 | |
| 7 | 3099 | 246.54 | 245.21 | 5.84 | 100.38 | 100.61 |
| | 2957 | 235.24 | | 5.86 | 100.73 | |
| | 3191 | 253.86 | | 5.86 | 100.73 | |
| 28 | 3875 | 308.27 | 307.16 | 5.72 | 98.32 | 98.89 |
| | 3844 | 305.81 | | 5.74 | 98.66 | |
| | 3864 | 307.40 | | 5.80 | 99.69 | |
| 56 | 5674 | 451.39 | 406.36 | 5.73 | 98.56 | 98.40 |
| | 4261 | 338.98 | | 5.80 | 99.68 | |
| | 5389 | 428.72 | | 5.64 | 96.96 | |

# APPENDIX C

# DRAFT SPECIFICATION FOR CONTROLLED LOW-STRENGTH MATERIAL

## 1. Scope

1.1 This specification covers ready-mixed controlled low-strength material (CLSM) manufactured and delivered to a purchaser in a freshly mixed and unhardened state as hereinafter specified. Requirements for quality of CLSM shall be either or as hereinafter specified. This specification does not cover placement, curing, or protection of CLSM after delivery to the purchaser.

1.2 The values stated in inch-pound units are regarded as standard.

1.3 As used throughout the specification the manufacturer shall be the contractor, subcontractor, supplier, or producer who furnishes the ready-mixed CLSM. The purchaser shall be the owner or representative thereof.

1.4 The text of this standard references notes and footnotes which provide explanatory material. These notes and footnotes (excluding those in tables) shall not be considered as requirements of the standard.

## 2. Referenced Documents

ASTM D 4832 Test Method for Preparation and Testing of Soil-Cement Slurry Test Cylinders

ASTM D 5971 Standard Practice for Sampling Freshly Mixed Controlled Low-Strength Material

ASTM D 6023 Standard Test Method for Unit Weight, Yield, Cement Content, and Air Content (Gravimetric) of Controlled Low Strength Material (CLSM)

ASTM D 6024 Standard Test Method for Ball Drop on Controlled Low Strength Material (CLSM) To Determine Suitability for Load Application

ASTM D 6103 Standard Test Method for Flow Consistency of Controlled Low Strength Material (CLSM)

Tennessee Department of Transportation (TDOT), Standard Specifications for Road and Bridge Construction

## 3. Basis of Purchase

3.1 The basis of purchase shall be the cubic yard of freshly mixed and unhardened CLSM as discharged from the mixer.

3.2 The volume of freshly mixed and unhardened CLSM in a given batch shall be determined from the total mass of the batch divided by the mass per unit volume of the CLSM. The total mass of the batch shall be calculated either as the sum of the masses of all materials, including water, entering the batch or as the net mass of CLSM in the batch as delivered. The mass per unit volume shall be determined in accordance with Test Method D 6023 from the average of at least three measurements. Each sample shall be taken in accordance with D 5971.

Note 1 – It should be understood that the volume of hardened CLSM may be, or appear to be, less than the expected due to waste, spillage, over-excavation, movement of forms, and some loss of entrained air or subsidence, none of which are the responsibility of the producer.

## 4. Ordering Information

4.1 The purchaser shall specify which of options A, B, or C shall be used as a basis for determining the proportions of the CLSM to produce the required quality. As defined herein, there are four (4) types of CLSM: excavatable flowable fill, air-entrained excavatable flowable fill, general use CLSM, and early strength flowable fill.

(A) Excavatable flowable fill (EFF) – When specified on the plans, an EFF shall be designed, proportioned, and delivered to the project meeting the following performance requirements:

| Property | Specification Limit |
|---|---|
| Load Application (ASTM D6024) | 24 hours maximum in any condition |
| Consistency (ASTM D 6103) | 8" minimum |
| Compressive strength (ASTM D 4832) [1] | 30-psi minimum at 28-days |
| Compressive strength (ASTM D 4832) [1] | 110-psi maximum at 98-days or 160-psi maximum at 364-days |

[1]- ASTM D 4832 procedure as modified in section 6

Specifiers should be aware that EFF designs will take longer periods of time to have sufficient bearing strength before backfilling is allowed. Each consistency test shall represent up to one hundred cubic yards of flowable fill at each installation.

The ready mix producer must complete a test trench (at least 3' wide x 3'deep x 8' long), during the mixture design process, with the proportioned materials to demonstrate the mixture will meet the performance criteria. The mixture

design may be adjusted with approval by the Engineer to obtain the required properties.

(B) Air-entrained Excavatable flowable fill (AEFF) – When specified on the plans, an EFF shall be designed, proportioned, and delivered to the project meeting the following performance requirements:

| Property | Specification Limit |
|---|---|
| Air content (ASTM D 6023) | Minimum 20 percent<br>Maximum 30 percent |
| Load Application (ASTM D6024) | 24 hours maximum in any condition |
| Consistency (ASTM D 6103) | 8" minimum |
| Compressive strength (ASTM D 4832) [1] | 30-psi minimum at 28-days |
| Compressive strength (ASTM D 4832) [1] | 110-psi maximum at 98-days or<br>185-psi maximum at 364-days |

[1] - ASTM D 4832 procedure as modified in section 6

Specifiers should be aware that EFF designs will take longer periods of time to have sufficient bearing strength before backfilling is allowed. Each consistency test shall represent up to one hundred cubic yards of flowable fill at each installation.

The ready mix producer must complete a test trench (at least 3' wide x 3'deep x8' long), during the mixture design process, with the proportioned materials to demonstrate the mixture will meet the performance criteria. The mixture design may be adjusted with approval by the Engineer to obtain the required properties.

Note 2 – Air-entrained EFF mixtures have little or no bleeding and do not appreciably consolidate and subside. Air-entrained EFF mixtures may be preferable where bleed water could cause problems or conditions impede bleed water loss.

(C) General Use CLSM: When not otherwise specified in the plans, or Contract, all flowable fill_shall be general use and shall be proportioned to meet the following:

| Property | Specification Limit |
|---|---|
| Load Application (ASTM D6024) | 24 hours maximum in any condition |
| Consistency (ASTM D 6103) | 8" minimum |

Note 3 - The above proportions may be adjusted by the Engineer to obtain the consistency required for satisfactory flow. Each consistency test shall represent up to one hundred cubic yards of flowable fill at each installation.

(D) **ZOOM!** Early strength flowable fill (ESFF) - When specified on the plans ESFF shall be designed, proportioned, and provided that meets the following performance specifications:

| Property | Specification Limit |
|---|---|
| Air content (ASTM D 6023) | Maximum 30 percent[1] |
| Load Application (ASTM D6024) | 6 hours maximum in any condition |
| Consistency (ASTM D 6103) | 8" minimum |
| Compressive strength (ASTM D 4832)[2] | 30-psi minimum in 24-hours |

[1]- when using air entrained mixture design
[2]- ASTM D 4832 procedure as modified in section 6

The proportions of ESFF shall include sufficient amounts of cementitious materials, high range water reducers, accelerators, and other chemical admixtures so the ESFF can be loaded/backfilled as specified. Each consistency test shall represent up to one hundred cubic yards of flowable fill at each installation.

The ready mix producer must complete a test trench (at least 3' wide x 3'deep x 8' long), during the mixture design process, with the proportioned materials to demonstrate the mixture will meet the performance criteria. The mixture design may be adjusted with approval by the Engineer to obtain the required properties.

The Contractor shall furnish certification that all flowable fill delivered to the project has been batched in accordance with the approved mixture design and meets the designated properties as specified. Chemical Additives and/or Air Entraining Admixture may be used to produce the desired consistency with no additional payment to be made for such additives.

## 5. Materials

5.1 Materials used in the placement of CLSM (flowable fill) shall meet the following requirements:

| Material | Subsection |
|---|---|
| Fine Aggregate | 903.01(f) except gradation shown below |
| Portland Cement, Type I | 901.01 |
| Fly Ash, Class C or Class F | 918.31 |
| Ground granulated blast furnace slag (GGBFS) | 918.32 |
| Water | 918.01 |
| Chemical Additives | 918.09 |
| Air Entraining Admixtures | 918.09 |

**CLSM Aggregate Gradation Requirements**

| Sieve Size | Total Per Cent Passing by Weight |
|---|---|
| 3/8-inch | 100 |
| No. 200 | 0-21 |

## 6. Modifications to ASTM D 4832-95$^{\varepsilon 1}$

6.1. Change the preferred mold from 6-in. diameter, 12-in. high rigid plastic (ASTM D 4832-95$^{\varepsilon 1}$ Section 6.1) to 4-in. diameter, 8-in. high single-use, wax-coated cardboard.

Note 4 – Past research at Tennessee Technological University has shown that less cylinder damage occurs during demolding when using cardboard molds.

6.2. Delete the last sentence of ASTM D 4832-95$^{\varepsilon 1}$ Note 4 and the second sentence of Section 10.1.

Note 5 - Past research at Tennessee Technological University has shown that EFF cylinders are far too easy to damage to allow mounding of the top and subsequent removal of the mound with a wire brush.

6.3. Insert 10.1.4. The preferred capping method for EFF is wet suit neoprene restrained in rigid retainers as described in Sauter, H. J. and Crouch, L. K., **"An Improved Capping Technique for Excavatable Controlled Low Strength Material Compressive Strength Cylinders,"** Journal of Testing and Evaluation, JTEVA, Vol.28, No.3, May 2000, pp. 143-148.

Note 6 – The research described in the paper indicates that the recommended capping technique yields more realistic compressive strengths than the ASTM D 4832-95 approved methods. In addition, the recommended method is either statistically or logistically superior (in most cases both) to the ASTM D 4832-95 approved capping methods.