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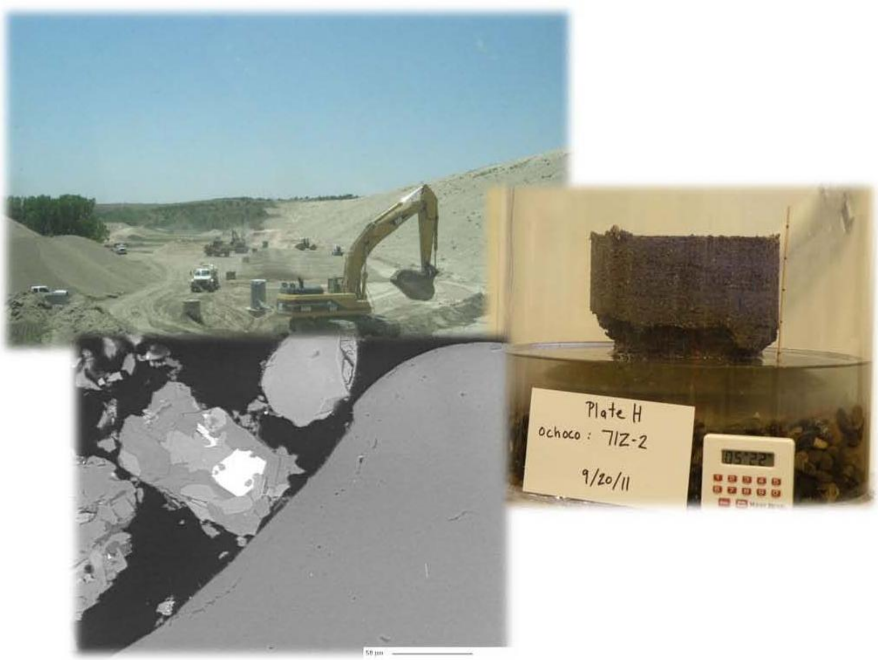
Report DSO-12-01

Development of a Test to Determine Cementation Potential of Embankment Dam Granular Filter Material – Results of Phase III Research

Dam Safety Technology Development Program



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14. ABSTRACT
Granular filters are used in embankment dams to protect against internal erosion either through the embankment or the foundation. For proper performance, it is required that the filter material not be able to sustain a crack during embankment settlement or seismic loading. Historically, the mechanism used to limit cracking potential is a restriction of no more than 5% nonplastic fines, and this requirement is easily measured with the standard soil tests for grain size distribution (gradation) and plasticity (Atterberg Limits). Unfortunately, material meeting this requirement has been observed to cement, and hence has cracking potential. More robust test procedures are needed in order to better quantify the desired material properties (cementation potential), and to this end, modification of the Vaughan and Soares Sand Castle Test has been undertaken jointly by the Bureau of Reclamation and U.S. Army Corps of Engineers. This report presents the third phase of the research, describing specimen preparation and test procedures and results from 16 source materials from around the United States. All materials met ASTM C-33 fine aggregate gradation requirements as well as the additional requirement of less than 2% fines. Additionally, unconfined compression tests were performed on each material to help quantify the strength gain from cementation. The Sand Equivalency Value, which further quantifies the amount and characteristics of the clayey portion of a material, was also determined for all sources to see how well it correlated with the Modified Sand Castle Test results. The Modified Sand Castle Test is shown to be a good indicator of cementation potential and correlates well with unconfined compressive strength, but to a lesser degree with sand equivalency value. Petrographic analysis aided in understanding the cementation mechanisms. A discussion is presented describing how the tests results could be carried forward into practice.

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Prepared by

Robert V. Rinehart, Ph.D., P.E.

U.S. Department of the Interior
Bureau of Reclamation
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Materials Engineering and Research Laboratory
Civil Engineering Services Division
Denver, Colorado

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Report DSO-12-01

Development of a Test to Determine Cementation Potential of Embankment Dam Granular Filter Material – Results of Phase III Research

Prepared: Robert V. Rinehart, Ph.D., P.E.
Materials Engineering and Research Laboratory, 86-68180

Checked: Bethany N. Jackson, P.E.
Materials Engineering and Research Laboratory, 86-68180

Technical Approval: Mark Pabst, P.E.
United States Army Corps of Engineers, Risk Management Center

Peer Review: Thomas R. Strauss, P.E.
Materials Engineering and Research Laboratory, 86-68180

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Date

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Date	Description	Prepared	Checked	Technical Approval	Peer Review

Acronyms

AOR	angle of repose
ASTM	American Society for Testing and Materials, International
cm	centimeter(s)
cm^3	cubic centimeters
C_u	Coefficient of Uniformity
EDS	Energy Dispersive X-ray
FEMA	Federal Emergency Management Agency
FM	Fineness Modulus
ft^3/s	cubic feet per second
in	inch(es)
kPa	kilopascals
min	minute(s)
MSCT	Modified Sand Castle Test
pcf	pounds per cubic foot
Reclamation	Bureau of Reclamation
SEM	Scanning Electron Microscope
SEV	Sand Equivalency Value
UCS	Unconfined Compressive Strength

Symbols

°C	degrees Celsius
°F	degrees Fahrenheit

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1.0 INTRODUCTION

Granular filters are used in embankment dams to protect against migration of fine-grained core or foundation materials that could lead to internal erosion (piping) failures and to provide drainage to relieve excess pore pressures that may build up in the embankment. Detailed guidance regarding the design, installation, and applications for embankment filters is available from several agencies (e.g., Federal Emergency Management Agency [FEMA], 2011; Bureau of Reclamation [Reclamation], 2007).

Embankment filters are particularly important in areas with seismic hazards and in cases where the embankment may desiccate or differentially settle, as core material may become cracked, creating the potential for uncontrolled seepage and erosion. It is critical that the filter zone not be able to sustain a crack. Accordingly, it is important to ensure that the granular filter material not exhibit cohesive or cemented behavior. Early consideration of this issue led to a requirement that filter materials not contain more than 5% fines (post-compaction) and that the fines be non-plastic. While this requirement does limit the potential for cohesive behavior, it is suspected that even smaller amounts of fines may lead to cohesive behavior and that other binding agents such as soluble minerals can result in cementation of granular filter sands. It is also suspected that non-plastic fines (i.e., dust from crushing operations, rock flour, and glacial flour) may lead to cementation.

Experience has shown that in the field, embankment filters can suffer from cementation. Excavation into the filter zone of one particular embankment dam revealed material so strongly cemented (bound) that it withstood blows by a hand shovel. The filter material also had sufficient strength to stand as an overhang. This cementing problem can be particularly prevalent in the Western U.S. where high daytime temperatures “cure” the soil. Based on this apparent problem of filter cementation, test procedures beyond the original grain size and plasticity tests are needed to ensure that filter materials will perform as desired and not exhibit cementitious or cohesive behavior.

An index-type test to measure cohesion potential of granular materials, known as the Sand Castle Test, was developed by researchers at the University of London in the 1970s and 80s (Vaughan et al., 1982). The test involved hand tamping a moist sand sample into a plastic cup, extracting the specimen, and submerging it in water. After the material collapsed under water, the submerged angle of repose (AOR) of the material was measured and compared to the AOR of the same dry material in air. If the submerged AOR was greater than the AOR in air, the material was deemed to have cohesive capability and unsuitable for use as a filter material. However, the test is only loosely described in the literature, compaction parameters are unclear, and precise criteria for evaluating materials were not established.

Additional work has been performed to duplicate and improve on the original Sand Castle Test (Yamaguchi, 2001; Park, 2003; Bolton et al., 2005, and McCook, 2005). However, these revisions still appear deficient in their specimen preparation techniques to mimic field behavior, and they are not sensitive enough to distinguish subtle changes in cementation potential. Of particular concern is the recognition that cementation has not been given the opportunity to develop. During construction, filter sand is typically compacted with vibratory rollers in a moist to wet state and then allowed to dry out in temperatures that can be in excess of 50 °C (120 °F) – conditions that may be favorable for cementation. Just such conditions have led to the observation of "crispy" filters (i.e., material that appears and feels cemented to the touch).

The research presented here, undertaken jointly by the Bureau of Reclamation Dam Safety Technology Development Program and the U.S. Army Corps of Engineers Risk Management Center, is aimed at developing a new index test to determine a granular material's cementation potential. Note that here, cementation is used to mean strength gain leading to the ability to sustain a crack. The new test is referred to as the Modified Sand Castle Test (MSCT). It is anticipated that the test will be a beneficial tool for engineers to use to screen candidate filter materials as well as to potentially provide qualitative criteria for construction specifications.

To date, the research has consisted of three phases, with the testing procedures being refined between each phase based on the results obtained. Additional materials have also been added to the study as the research has progressed. Phase II progress and results were documented in Dam Safety Office Report DSO-11-04. The latest research included herein summarizes Phase III of the studies. Specimen preparation methods and test procedures are described in detail. MSCT results for 16 granular filter sands from across the U.S. are presented, and correlations between the MSCT and other index and physical property tests are discussed. Further, the results of a petrographic examination of selected samples are presented.

2.0 MODIFIED SAND CASTLE TEST PROCEDURE

The MSCT consists of two main components: (1) specimen preparation and (2) incremental soak testing. The general approach taken is to compact the specimens in a saturated condition and then dry them to constant mass before wetting them and recording the amount of time it takes for the specimen to collapse. Each portion of the procedure is described in more detail below.

2.1 Specimen Preparation

The specimen preparation procedures were developed to favor the development of cementation and to be within plausible bounds of field conditions. The tested materials were washed and sieved to meet the gradation requirements of ASTM C33 fine aggregate (sand), except adding the additional requirement that the percent passing the No. 200 sieve not exceed 2% (pre-compaction). The C33 concrete sand gradation was selected because it has shown to be an effective general filter material and is suitable for a wide range of commonly encountered embankment and foundation base soils. Following washing and verification of gradation, each specimen was wetted to saturation and compacted to maximum index unit weight with a vibrating hammer according to ASTM D7382-08 (see figure 1). Denver, Colorado, tap water was used for both washing and wetting. The compaction mold used was a modified Proctor cylindrical split mold, 2,124 cm^3 (0.075 ft^3) in volume, 15.25 cm (6 in) in diameter, and 11.64 cm (4.58 in) in height as specified by ASTM D7382. This vibratory compaction approach was chosen over impact (Proctor) compaction as it subjects the soil to less particle breakage and more closely mimics the way granular materials are compacted in the field (e.g., with vibratory smooth drum rollers). Specimens were compacted in three equal height lifts with 60 seconds of vibratory compaction effort provided to each lift. Once compacted, the specimens were immediately removed from the split mold and dried to constant mass in a 50 °C (120 °F) oven. This temperature was chosen based on observed ground temperatures for summertime fill placement in the western U.S. Four test specimens (replicates) of each material were prepared. Additional specimens were prepared as necessary to ensure that the dry density of the tested specimens agreed within ±2%.

2.2 Incremental Soaking Test Procedure

The apparatus used for the incremental soaking portion of the test consisted of a cylindrical acrylic chamber with plumbing at the bottom to allow the introduction of water (see figure 2a). The chamber was partially filled with gravel to ensure an evenly distributed and laminar flow of water into the chamber. A brass ring was embedded in the gravel and acted as a leveling base for the specimens. Each specimen was placed atop the brass ring on a perforated acrylic disk and carefully leveled (figure 2b).

After the specimen was leveled, water was introduced from the bottom of the chamber. Owing to the perforated base plate, water accessed the specimen from the bottom and sides. Previous research showed when the water level was maintained at a depth of 2.5 cm (1 in), specimen collapse for some materials could take several months [DSO-11-04]. Therefore, it was decided that the water level should be incrementally increased at set time intervals to accelerate the test.

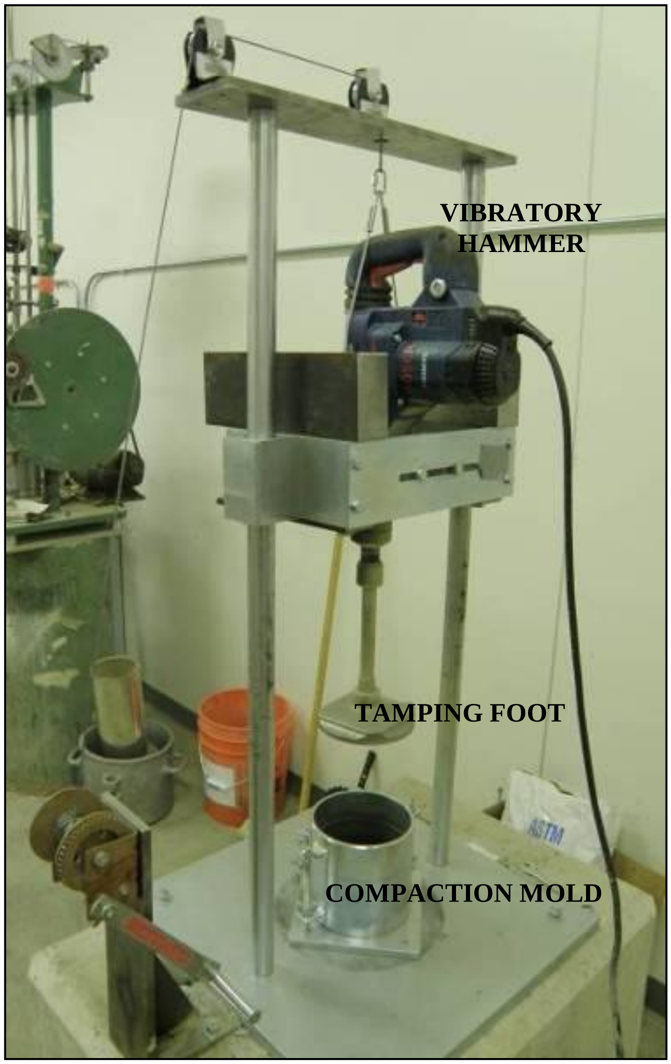

Figure 1.—Vibratory hammer compaction apparatus.

A duration of 24 hours was deemed to be an appropriate maximum test duration. This methodology is referred to as incremental soaking and is outlined below:

1. Once the specimen was placed inside the chamber, water was introduced from the bottom of the chamber to a depth of 2.5 cm (1 in) up the specimen. The timer was started once the water reached the 2.5 cm mark. The water was maintained at this initial depth for the first 20 minutes of testing. In general, specimens absorbed water due to capillary action and crumbled or eroded from the base of the specimen towards the top (figure 2c). Some materials were observed to completely collapse or disintegrate during this first 20 minutes.

2. In cases where the specimen was still intact after an elapsed time of 20 minutes, the water level was increased to 5 cm (2 in).

3. The water level was further increased to completely submerge the specimen if the specimen was still intact after a total of 100 minutes had elapsed since the start of the test (i.e., 20 min with water at 2.5 cm [1 in] depth and 80 additional minutes with the water at 5 cm [2 in] depth).

4. Timing was continued until the specimen collapsed or until an elapsed time of 24 hours was reached (i.e., the specimen fully submerged for 22 hours and 20 minutes), at which time the test was terminated and the condition of the specimen noted.

The manner in which a specimen failed was carefully noted for all tests. Often, failure (i.e., collapse, complete disintegration) consisted of the specimen breaking into several chunks along nearly vertical lines. In other cases, specimens would topple over due to instability at the base of the specimen. It was also common for a large piece of material to fall off one side, causing the specimen to topple due to imbalance. For all materials, tests were repeated as necessary until a consistent failure type had been established for the material, and it was judged that variability in specimen preparation and placement in the chamber were not contributing to the variability of the results.

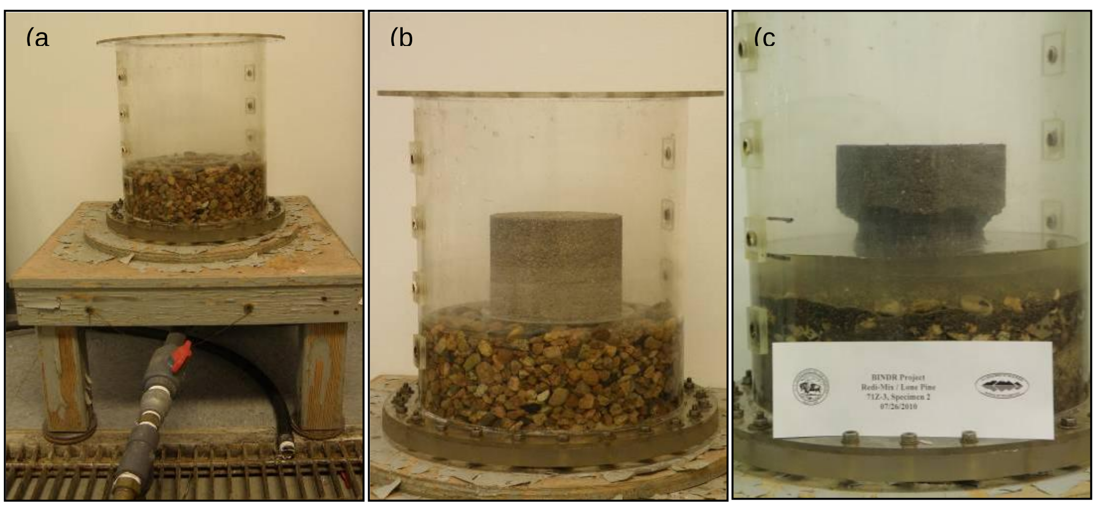

Figure 2.—(a) Incremental soaking apparatus, (b) specimen on acrylic disk before introduction of water, and (c) test in progress with 2.5-cm deep water.

3.0 MATERIALS TESTED

As summarized in table 1, 16 filter materials were tested, all meeting the gradation requirements for C33 fine aggregate. All materials were washed to remove fines such that the materials met the additional requirement of less than 2% fines. The recycled (crushed) concrete (index No. 71Z-1) and Colorado Silica Sand (index No. 36F-1136) were chosen to serve as the controls for high and low cementation potential, respectively, based on previous studies. Twelve materials were from commercial sources: three from Florida (71Z-7, -8, and -9), four from California (36F-1138, -1139, -1140, and -1141), and five from Oregon (71Z-3, -4, -5, -6, and -10). Two materials were from undeveloped borrow sources: one from California (36F-1137) and one from Oregon (71Z-2). Gradation plots for each material are available in appendix B.

Table 1.—Summary of materials tested

Lab index number	Source	Origin	Location
36F-1136	Carmuse Industrial Sands	Natural silica sand	CO
36F-1137	Basalt Hill (undeveloped borrow source)	Manufactured basalt sand	CA
36F-1138	Teichert Aggregate	Hope Creek	CA
36F-1139	Marks & Sons , Inc.	Orestimba Creek alluvium	CA
36F-1140	Triangle Rock Products	Los Banos Creek alluvium	CA
36F-1141	Granite Rock	Manufactured granite sand	CA
71Z-1	Concrete Recyclers	Crushed roadway concrete	CO
71Z-2	Ochoco Dam, Zone 2 borrow material	Manufactured sand of alluvial origin	OR
71Z-3	Lone Pine	Crooked River alluvium	OR
71Z-4	Shevlin Sand & Gravel	Deschutes River alluvium	OR
71Z-5	Grizzly Rock Products	Crooked River alluvium (Upper Terrace)	OR
71Z-6	Rock Products Manufacturing	Crooked River alluvium (flood plain)	OR
71Z-7	Lake Wales Mine	Natural silica sand	FL
71Z-8	FEC Quarry	Manufactured limestone sand	FL
71Z-9	Immokalee Mine	Natural silica sand	FL
71Z-10	Hooker Creek Companies, LLC	Glacial outwash (Ochoco Drainage)	OR

4.0 RESULTS

4.1 Modified Sand Castle Test Results

The goal of the test being developed is to assess a candidate filter material's cementation potential. This result, in addition to existing basic laboratory tests, would help define a material's suitability for use in embankment filter applications. To aid in interpreting the test results, a class system was devised. Essentially, the more rapidly a material collapses, the lower the class it is assigned and higher the quality it is ascribed. Preference was given to materials that collapsed within 5 minutes of introduction of water or increase of water depth. Based on the results of the 16 materials tested, and along with insight gained from previous research, the following six classes were proposed:

- *Class I*: Collapse within 5 minutes of the introduction of 2.5 cm (1 in) of water
- *Class II*: Collapse within 20 minutes of the introduction of 2.5 cm (1 in) of water
- *Class III*: Collapse within 5 minutes of increasing the water level to 5 cm (2 in), 25 minutes total elapsed time
- *Class IV*: Collapse within 80 minutes of increasing the water level to 5 cm (2 in), 100 minutes total elapsed time
- *Class V*: Collapse within 5 minutes of fully submerging the sample
- *Class VI*: Collapse after 5 minutes of fully submerging the specimen or no collapse within 24 hours

Average MSCT failure times are tabulated for each material in table 2. Figure 3 graphically depicts the results. On figure 3, horizontal bars are shown to represent the range of failure times for each material (i.e., variation between specimens used to compute the average). Note that the plot is in log scale, causing the range in failure times for the Class I and II materials to appear exaggerated compared to the higher classes. All MSCT results (used to compute the averages) are available in appendix C. Specimen photographs are available in appendix A.

More research is needed before the MSCT can be used confidently in practice. However, the preliminary results presented here indicate that the MCST is sensitive to the wide range of cementation potential that exists among typical filter materials. It would be an easy extension of these results to establish criteria such as, for example, Class I and II materials can be confidently used, Class III and IV materials should be considered for use when cracking is not critical, and Class V and VI materials should be avoided in all cases.

Table 2.—Summary of results

Lab index number	Origin and location	$\gamma_{d, max}$ (pcf)	MSCT failure time (min)	MSCT class	SEV (%)	UCS (kPa)	C_u	FM
36F-1136	Natural silica sand, CO	111.9	4.3	I	95	13	2.34	2.41
36F-1137	Manufactured basalt sand, CA	120.3	24.3	III	95	112	7.50	3.05
36F-1138	Hope Creek alluvium,[1] CA	122.5	37.0	IV	80	260	7.26	2.98
36F-1139	Orestimba Creek alluvium, CA	113.7	7.9	II	78	67	6.28	3.01
36F-1140	Los Banos Creek alluvium, CA	113.6	26.7	IV	76	74	4.38	3.00
36F-1141	Manufactured granite sand, CA	117.0	22.4	III	96	57	6.80	2.86
71Z-1	Crushed roadway concrete, CO	96.2	1440.0[2]	VI	92	31	4.67	2.80
71Z-2	Manufactured sand of alluvial origin, OR	109.7	7.5	II	81	48	3.48	2.53
71Z-3	Crooked River alluvium, OR	112.2	9.3	II	88	30	4.45	2.50
71Z-4	Deschutes River alluvium, OR	113.1	28.3	IV	92	173	5.70	2.88
71Z-5	Crooked River alluvium (Upper Terrace), OR	109.3	17.7	II	89	30	3.48	2.54
71Z-6	Crooked River alluvium (flood plain), OR	105.5	20.4	III	90	50	4.20	2.58
71Z-7	Natural Silica sand, FL	112.5	1.3	I	100	3	3.53	2.58
71Z-8	Manufactured limestone sand, FL	110.5	100.5	V	95	240	6.67	2.81
71Z-9	Natural silica sand, FL	119.2	1.9	I	96	13	3.29	2.51
71Z-10	Glacial outwash (Ochoco Drainage),[1] OR	117.1	21.8	III	92	65	5.87	2.72

[1] Material is partially manufactured, containing about 20–30% crushed material.
[2] Specimens did not collapse; test terminated after 24 hours elapsed.

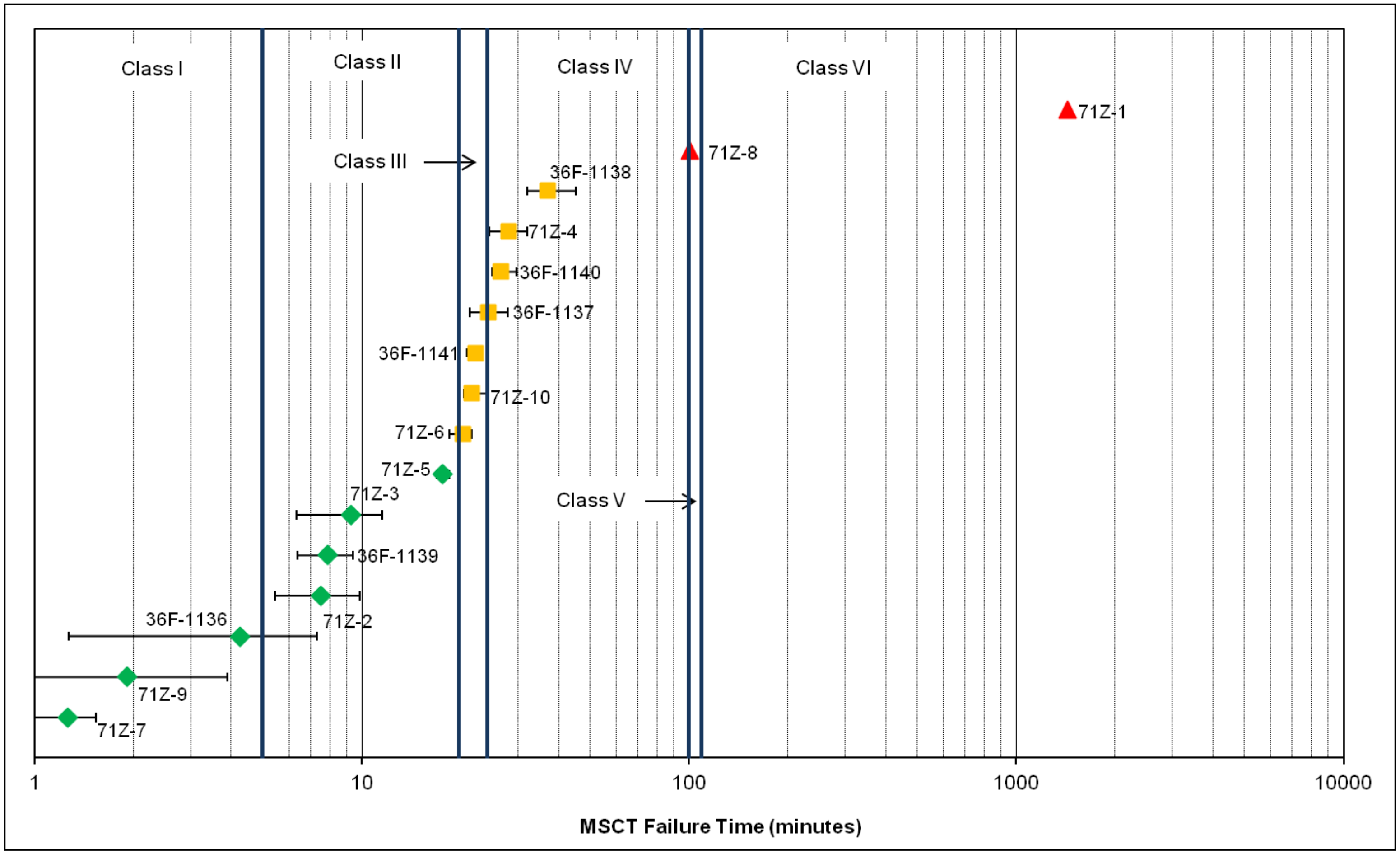

Figure 3.—Summary of MSCT failure times for materials tested with depiction of class designations.

4.2 Relationship to Other Index Properties

Various researchers have suggested the use of other index properties such as the Sand Equivalency Value (SEV) per ASTM D2419 and Unconfined Compressive Strength (UCS) per ASTM D1633 and D2166 as potential tests to screen candidate filter materials for cementing potential (e.g., McCook, 2005; FEMA, 2011). In addition to SEV and UCS, several other physical properties of the sand materials tested here were investigated to determine if any relationships existed between physical properties and cementation potential measured by the MSCT (see table 2). Physical properties investigated include the Coefficient of Uniformity, $C_u = D_{60}/D_{10}$, where D_{60} and D_{10} are the effective grain sizes corresponding to 60% and 10% finer in the grain size distribution curve, and the Fineness Modulus, FM, determined according to ASTM C136. Table 3 summarizes the average physical properties of interest for the six cementation classes. The index properties were determined from specimens of the same material used during MSCT testing. Individual UCS and SEV test reports are available in appendices D and E, respectively. UCS specimen photographs are available in appendix A.

Table 3.—Average physical properties for the six MSCT classes

MSCT class	Number of materials in class	Avg. SEV	Avg. UCS	Avg. C_u	Avg. FM
I	3	97	10	3.05	2.50
II	4	84	44	4.42	2.65
III	4	93	71	6.09	2.80
IV	3	83	169	5.78	2.95
V[1]	1	95	240	6.67	2.81
VI[1]	1	92	44	4.67	2.80

[1] Class is only represented by one material.

Figure 4 illustrates that an increase in C_u corresponds to an increase in cementation potential (i.e., MSCT failure time). Similarly, figure 5 shows the same trend exists for FM versus cementation potential. C_u and FM are simple characteristics describing the shape of the grain size distribution curve, and this trend is likely explained as a manifestation of grain size distribution: materials with higher values of C_u or FM are more well graded, which leads to more grain to grain contacts, which leads to stronger overall cementation. This trend is more pronounced for Classes I – IV. Classes V and VI are only represented by a single material, and the physical properties do not necessarily reflect what would be typical for the class. For this reason, the best-fit lines shown on figures 4 and 5 do not take Class V and VI materials into account.

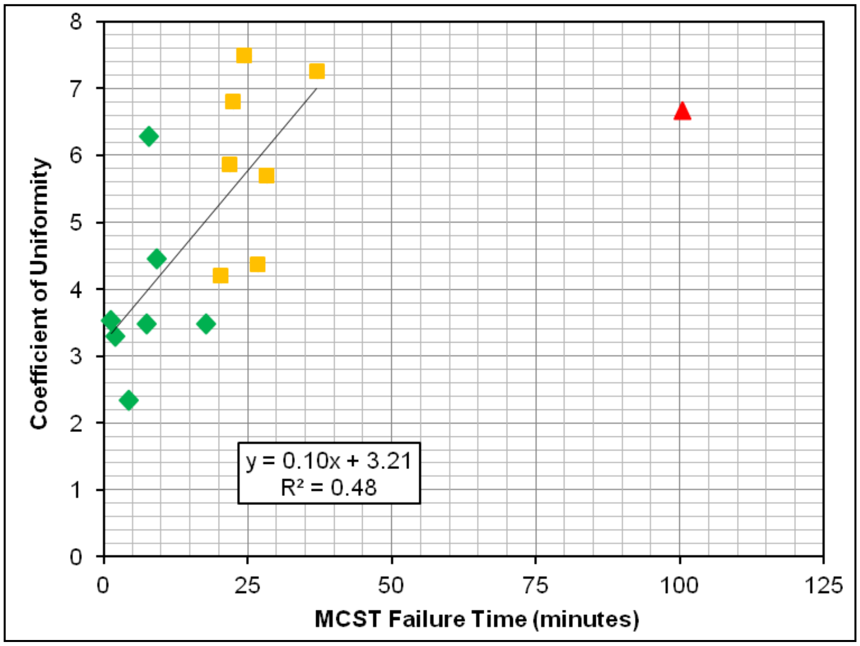

Figure 4.—Relationship between MSCT failure time and Coefficient of Uniformity, C_u. (Note: Best fine line exclusive of Class V and VI materials.)

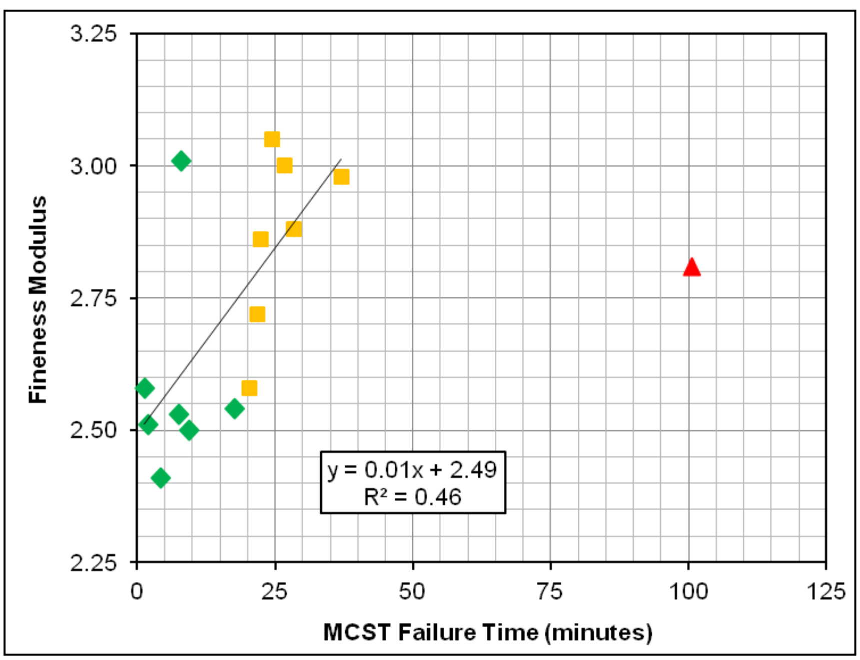

Figure 5.—Relationship between MSCT failure time and fineness modulus, FM. (Note: Best fine line exclusive of Class V and VI materials.)

As shown on figure 6, decreasing SEV generally leads to increased failure time for Classes I – IV, although this correlation is poor. The premise that granular filter materials can be evaluated based on SEV alone is not supported by the results presented here. Specifying a minimum value of SEV alone is likely not sufficient to screen out potentially cementitious filter sands.

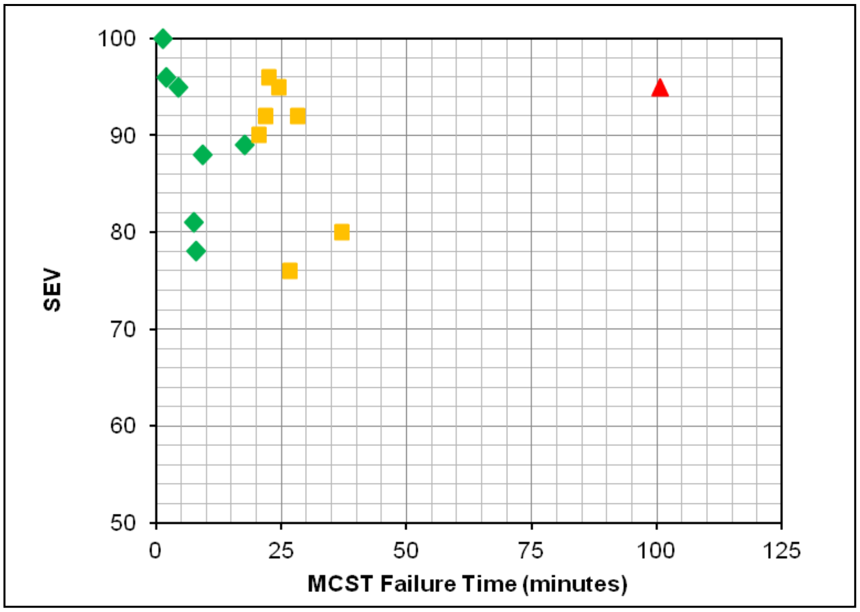

Figure 6.—Relationship between MSCT failure time and Sand Equivalency Value, SEV.

As shown on figure 7, a good correlation exists between strength gain due to cementation as gauged by UCS and cementation potential. The specimens used for UCS testing were prepared in the same manner as those for MSCT testing (see section 2.1), although a special split mold, 7.6 cm (3 in) in diameter by 17.1 cm (6.75 in) high (length:diameter ratio = 2.25), was used. The specimens were compacted in a saturated condition in three lifts using the vibratory hammer and an appropriately sized tamping foot. The vibration time per lift was varied from that specified in ASTM D7382 in order achieve a similar level of compaction (density) in the smaller mold as achieved by following ASTM D7382 in the modified Proctor mold. A vibration time of 15 seconds per lift was found to produce good agreement. After compaction, the UCS specimens were dried to constant mass in a 50 °C (120 °F) oven. UCS was determined in accordance with ASTM D1633 and D2166.

It is important to observe that the recycled concrete does not follow the trend for UCS versus MSCT failure time. Even though the recycled concrete is classified as a Class VI material and did not collapse after being submerged for 24 hours, it exhibited very minimal strength gain according to the UCS Test. This observation provides justification for using multiple test methods, rather than relying on a

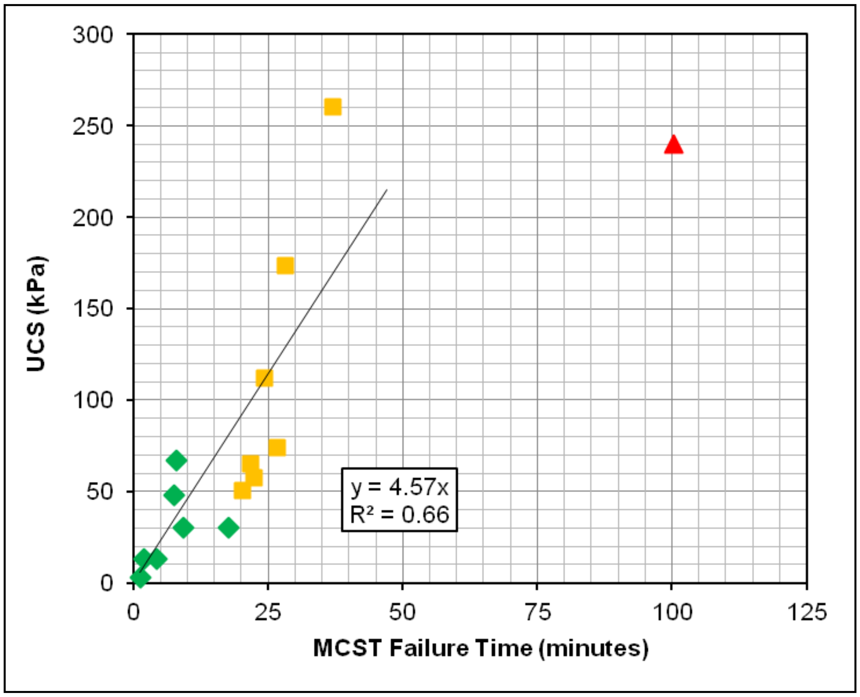

Figure 7.—Relationship between MSCT failure time and UCS. (Note: Best fine line exclusive of Class V and VI materials.)

single test, when screening potential materials for use in embankment filters. There are a variety of bonding mechanisms, and as demonstrated by the recycled concrete, they may not manifest equally in each test.

5.0 PETROGRAPHIC EXAMINATION

A petrographic examination was undertaken in an effort to clarify the cementing mechanisms present in the tested materials. The key results from the examination are discussed here, based on the full petrographic report in appendix F. Further discussion from an engineering perspective follows.

One material from each cementation class was submitted for petrographic examination, including: 36F-1136, -1137, 71Z-1, -2, -4, and -8. Submitted samples included both loose material and untested (intact) UCS specimens subjected to the specimen preparation technique described earlier. The petrographic examination consisted of megascopic and microscopic observations, including Petrographic and Scanning Electron Microscope (SEM), Energy Dispersive X-ray (EDS), and a few physical and chemical tests (see appendix F for additional details). Polished petrographic thin sections were fabricated as follows: Intact fragments from the UCS specimens were stabilized with epoxy, and the hardened epoxy impregnated fragment was cemented onto a glass slide, sectioned, and finely ground for viewing with both a petrographic microscope and SEM.

The thin sections represent an unoriented, two-dimensional slice of the specimen. Grain-to-grain relations may be referred to as concavo-convex contact, long contact, and/or point contact (figure 8). Any grains that appear suspended in the epoxy matrix (floating grains) are likely in grain-to-grain contact above or below the plane of the thin section.

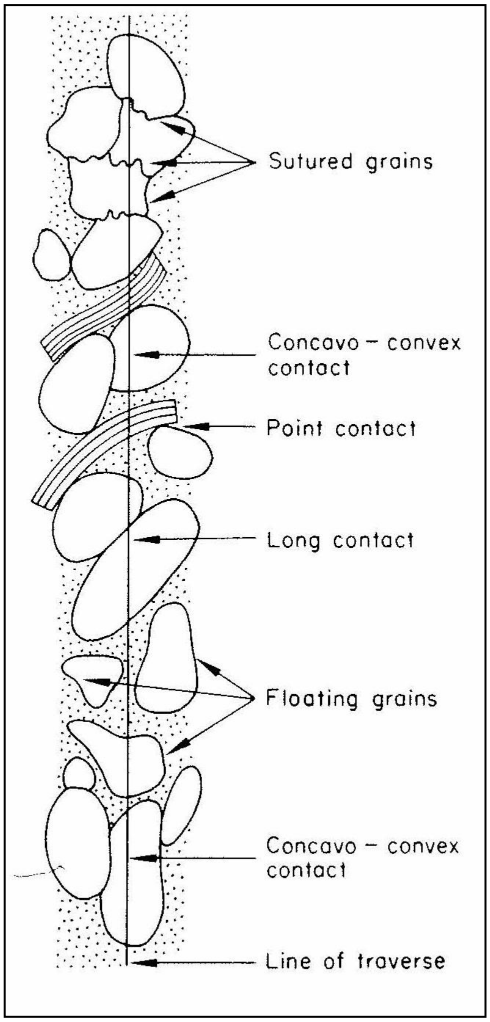

Figure 8.—Illustration of grain-to-grain contact types (illustration from Pettijohn, Potter, and Siever, 1972, *Sand and Sandstone*). Note that the bent and wavy particles represent mica and are shown for illustration only.

Petrographically, the specimens from MSCT Classes I – IV were classified as weakly cemented with fine aggregate bonds and tap water residue. The difference in sample stability for the observed weakly cemented samples (ranging from

MSCT Class I to IV) is likely controlled by the number of finer-sized mineral particles located at larger grain contacts and by the proportion of concavo-convex and long grain contacts. An increase in the number of smaller particles and in the proportion of concavo-convex and long contacts both serve to increase the grain contact surface area. This is in agreement with the correlations between MSCT and C_u and FM presented earlier, which indicated that more well-graded materials had higher cementation potential. Figures 9 and 10 show typically observed gain contacts for two materials – Basalt Hill, 36F-1137, MSCT Class III and Ochoco Zone II Pit Run, 71Z-2, MSCT Class II, respectively.

It is interesting that a similar mechanism to that just discussed is also discussed in the literature with respect to hydrocollapsible soils. Dudley (1970) presents a discussion of various mechanisms of temporary strength gain found in collapsible soils. He describes a process by which small particles (i.e., silt or clay size) are pulled into the wedges of space between larger grains through the evaporation of pore fluid. This results in the formation of clusters of randomly oriented particles that act as bridges or buttresses serving to support the larger grains. It follows that the re-introduction of water could dissolve these supports.

The petrographic examination also revealed that it is likely that the evaporation of the Denver tap water used during specimen preparation contributed some mineral residue at the grain contacts. Additional residue is also likely contributed from minute amounts of leaching or solutioning of the soluble minerals present in the sand grains. These small amounts of residue act as a binding agent (i.e., cement), serving to strengthen or weld together the inter-particle bonds. This strengthening effect of the residue binding agents likely increases with the grain contact surface area as discussed above. This finding is also corroborated by Dudley (1970) who discusses that iron oxides are a common source of particle bonding in collapsible soils. For illustration, figure 11 shows EDS results for the Ochoco Zone II Pit Run material (tap water residue filled voids) in contrast with EDS results from the FEC Quarry limestone sand (calcium carbonate filled voids).

The analysis performed here does not enable the determination of the definite sources of the mineral residue observed or the relative amounts coming from tap water versus solutioning or leaching. It is expected that the tap water would have a similar effect on all samples tested. Further, it is not anticipated that results would be significantly different if distilled water was used in specimen preparation, although this could easily be investigated.

The petrographic analysis revealed that the sample stability of the more strongly cemented specimens from MSCT Classes V and VI is likely controlled by the presence of numerous contact areas and gaps filled with calcium carbonate or carbonated Portland cement fines. Numerous calcium carbonate cemented contact areas filled limestone sand sample voids (see figure 11). Numerous carbonated Portland cement paste particles cemented contact areas and filled the recycled concrete voids.

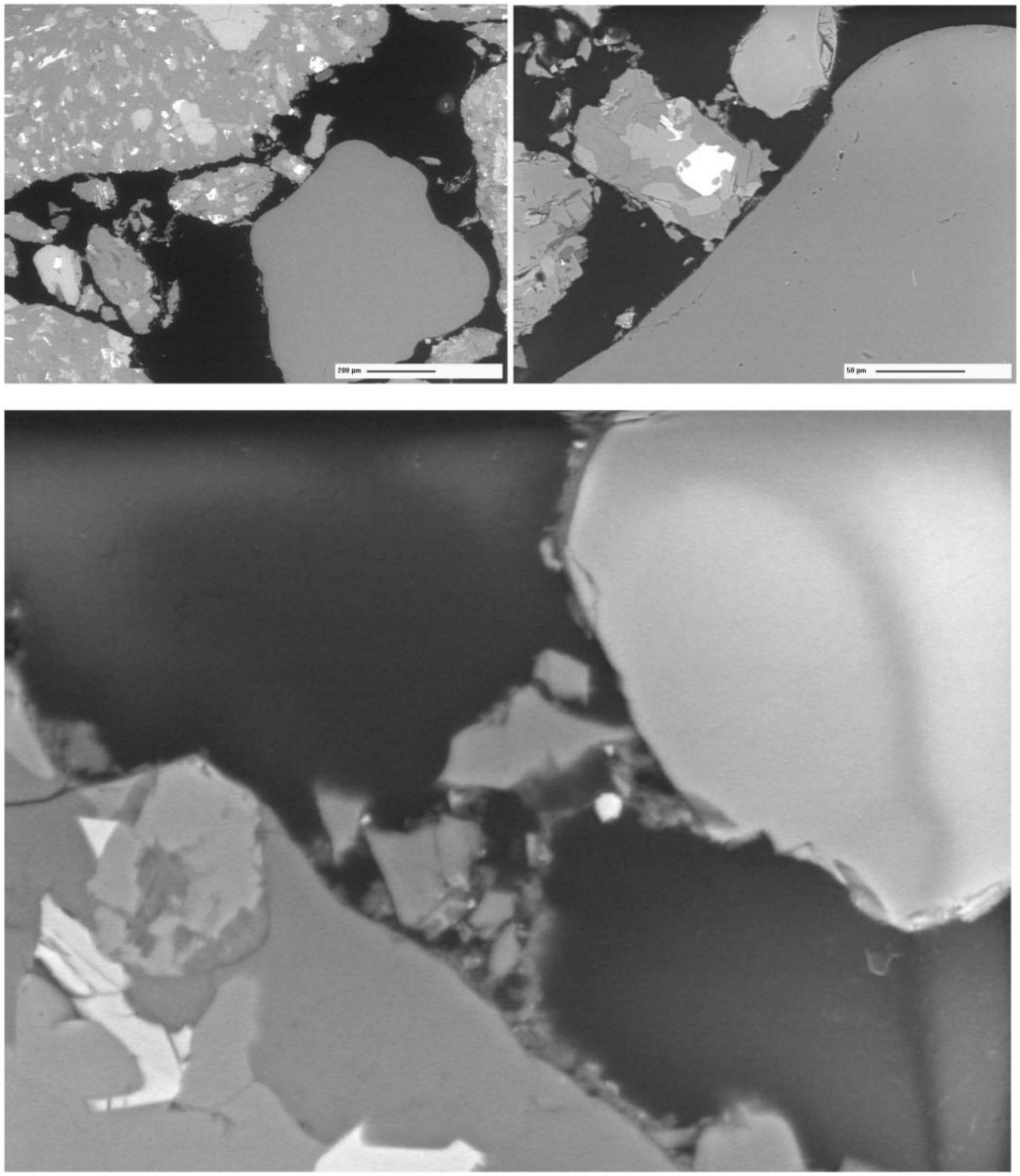

Figure 9.—SEM images of manufactured basalt sand (36F-1137). The grains are primarily in point contact. Direct contact between grains or contact by fine-grained aggregates appears to form a binder. The magnification is 100X (upper left), 500X (upper right), and 2,000X, with bar scales of 200 µm (upper left) and 50 µm (upper right), respectively. The higher magnification image shows fine particle bonds bridging grain contacts.

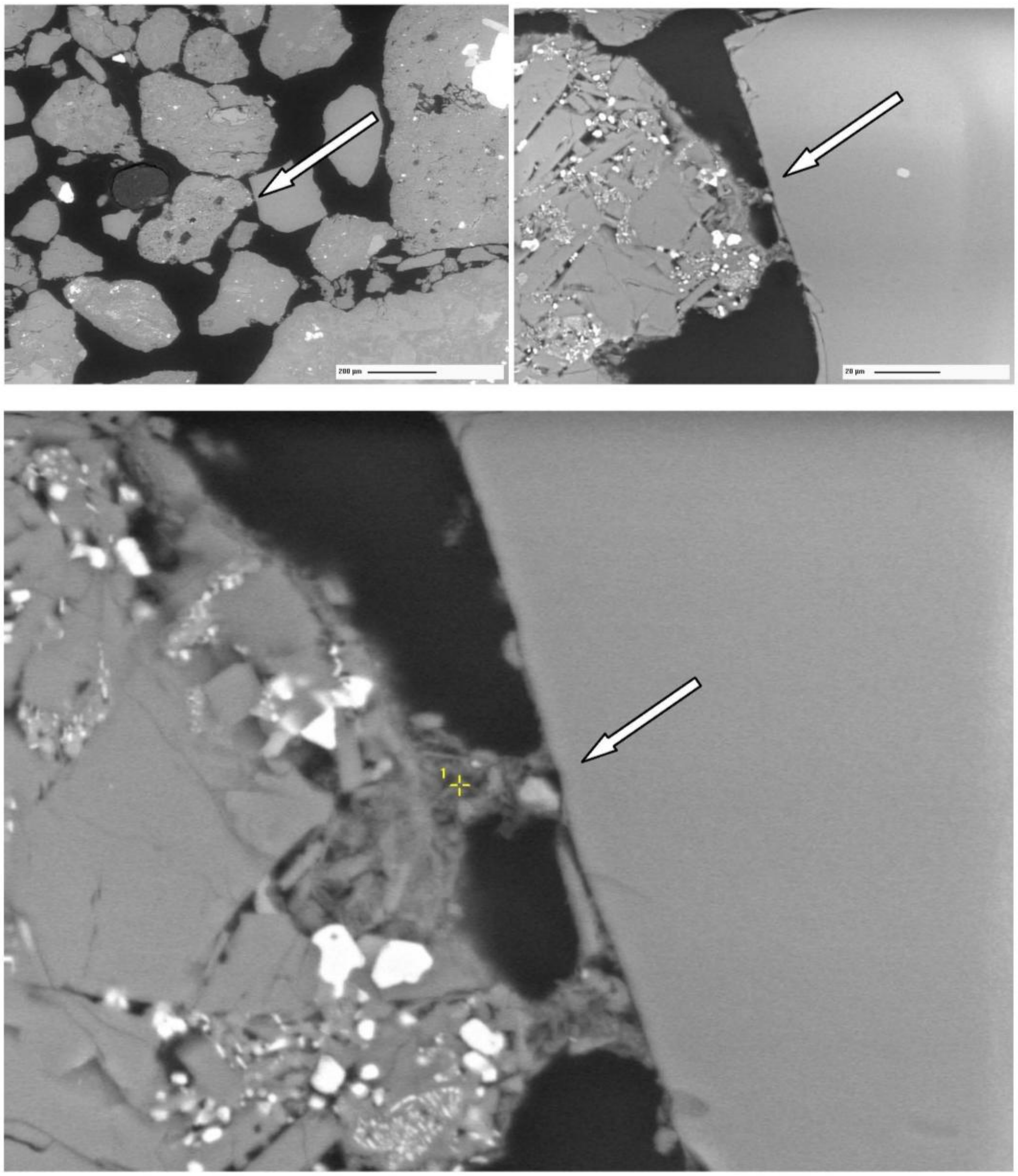

Figure 10.—SEM images from Ochoco Zone 2 borrow material (71Z-2). The grains are primarily in long and point contact. A binder is present at few grain contacts (arrow). The magnification is 100X (upper left), 1,000X (upper right), and 2,000X (lower) with bar scales of 200 µm (upper left) and 20 µm (upper right). The higher magnification image shows fine particle bonds at grain contacts. The yellow crosshair indicates the location of the EDS survey.

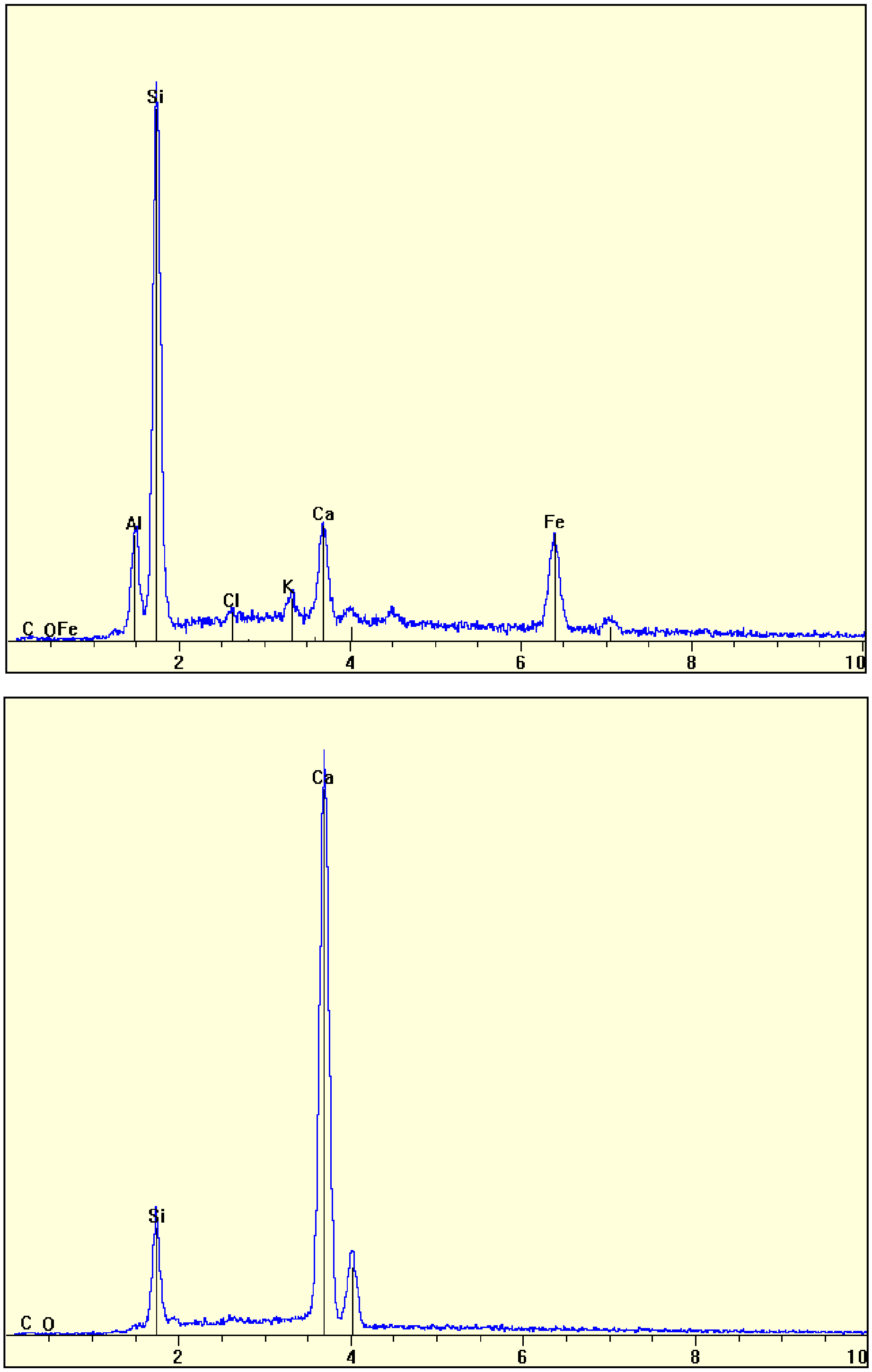

Figure 11.—EDS analysis indicates gap filling material in the manufactured basalt sand is likely rock and mineral particles and mineral residue from Denver tap water (top) in contrast with the EDS analysis from the limestone sand, which indicates calcium carbonate infilling (bottom). The graphs show intensity on the vertical axis and the x-ray energy (corresponding to elements) on the horizontal axis.

6.0 APPLICATIONS

Since the role of the filter is to protect against cracks that may develop in the dam, due to differential settlement, foundation discontinuities, desiccation, etc., similar cracking of the filter is not acceptable. The cracking potential of the filter medium should be evaluated during evaluation of existing dams, during the design phase for new dams, and/or modification of existing dams. Candidate filter materials could be tested using the tests described in this paper (MSCT, UCS, and SEV) to ensure that the cracking potential is within acceptable limits.

The test procedures described in this paper can then be used in two ways. The first would be to evaluate potential borrow areas or commercial sources during the design phase. Candidate materials that are capable of sustaining a crack, as indicated by these test procedures, would be eliminated from consideration and not listed in the specification (tender) documents provided to bidders. The other application of the procedures would occur when executing the work; namely, during submittal acceptance and quality control as the contract requirements are enforced during construction.

7.0 CONCLUSIONS

The research has demonstrated that the current specimen preparation and incremental soaking test procedures are sensitive to cementation potential. The specimen preparation techniques, including compaction to maximum density from a saturated state and drying in a 50 °C (120 °F) oven, encourage cementation while being within plausible field conditions. Based on these findings, MSCT testing in its current state appears to be an acceptable test procedure to screen candidate embankment filter materials for cementation potential.

A strong correlation between MSCT failure time and SEV was not found. A weak trend does exist such that a decreased value of SEV generally corresponds to increased cementation potential. A good relationship between UCS and MSCT failure time was found, with materials with higher cementation potential exhibiting higher strength. However, the recycled concrete material did not follow this trend. This provides a good illustration of why it is recommended to use the aggregated results of several tests (i.e., gradation, MSCT, SEV and UCS testing) when screening materials. Based on the current state of technology and understanding about the cementing mechanisms in granular filter materials, a single criterion (e.g., SEV > 80) should not be used to separate acceptable from unacceptable materials.

Petrographic examination revealed that an increase in strength corresponded to an increase in the grain contact surface area and that mineral residue (from tap water evaporation and solutioning) acted as a binder or cement at the grain-to-grain contacts.

8.0 FUTURE RESEARCH

Future research efforts that should be pursued in the development of the MSCT include testing additional material sources to further refine the six classes proposed here and the typical properties for materials in each class. Testing with lake water from the location where the filter will be installed may yield more realistic results and should be investigated. Similarly, in an effort to standardize the test, testing with distilled water should be investigated as well. Further refinement of the test could also include compacting specimens at different densities and drying at other temperatures to more closely mimic anticipated field conditions.

9.0 ACKNOWLEDGEMENTS

The authors are grateful for financial assistance provided by the U.S. Army Corps of Engineers, Risk Management Center and the Bureau of Reclamation Dam Safety Office Technology Development Program.

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APPENDICES

A MSCT and UCS Specimen Photographs

B Grain Size Distribution Reports

C MSCT Results

D UCS Results

E Sand Equivalent Test Reports

F Petrographic Memo (MERL-2012-16)

APPENDIX A

MSCT and UCS Specimen Photographs

Figure A-1.—Beginning of Sand Castle Test for Sample 36F-1136.

Figure A-2.—Sample has fully absorbed water and is being measured for 50% disintegration.

Figure A-3.—Sample shown prior to the UCS Test.

Figure A-4.—Sample showing failure plain after UCS Test.

Figure A-5.—Sample setup before test procedure.

Figure A-6.—Sample has fully absorbed water, but has not reached 50% disintegration. Test has extended beyond 20 minutes.

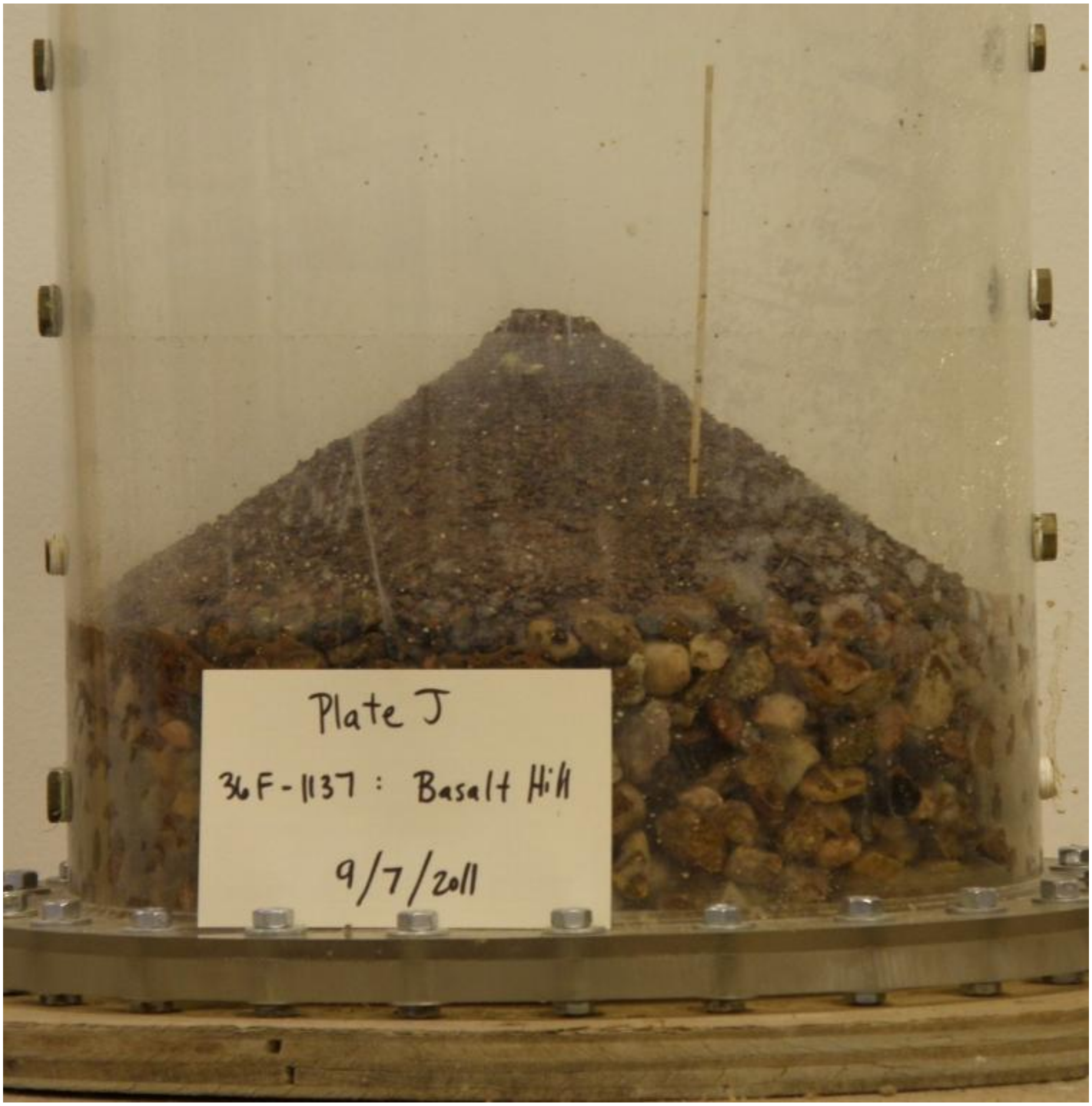


Figure A-7.—Sample at completion of Sand Castle Test.

Figure A-8.—Specimen prior to UCS Test.

Figure A-9.—Sample showing failure after UCS Test.

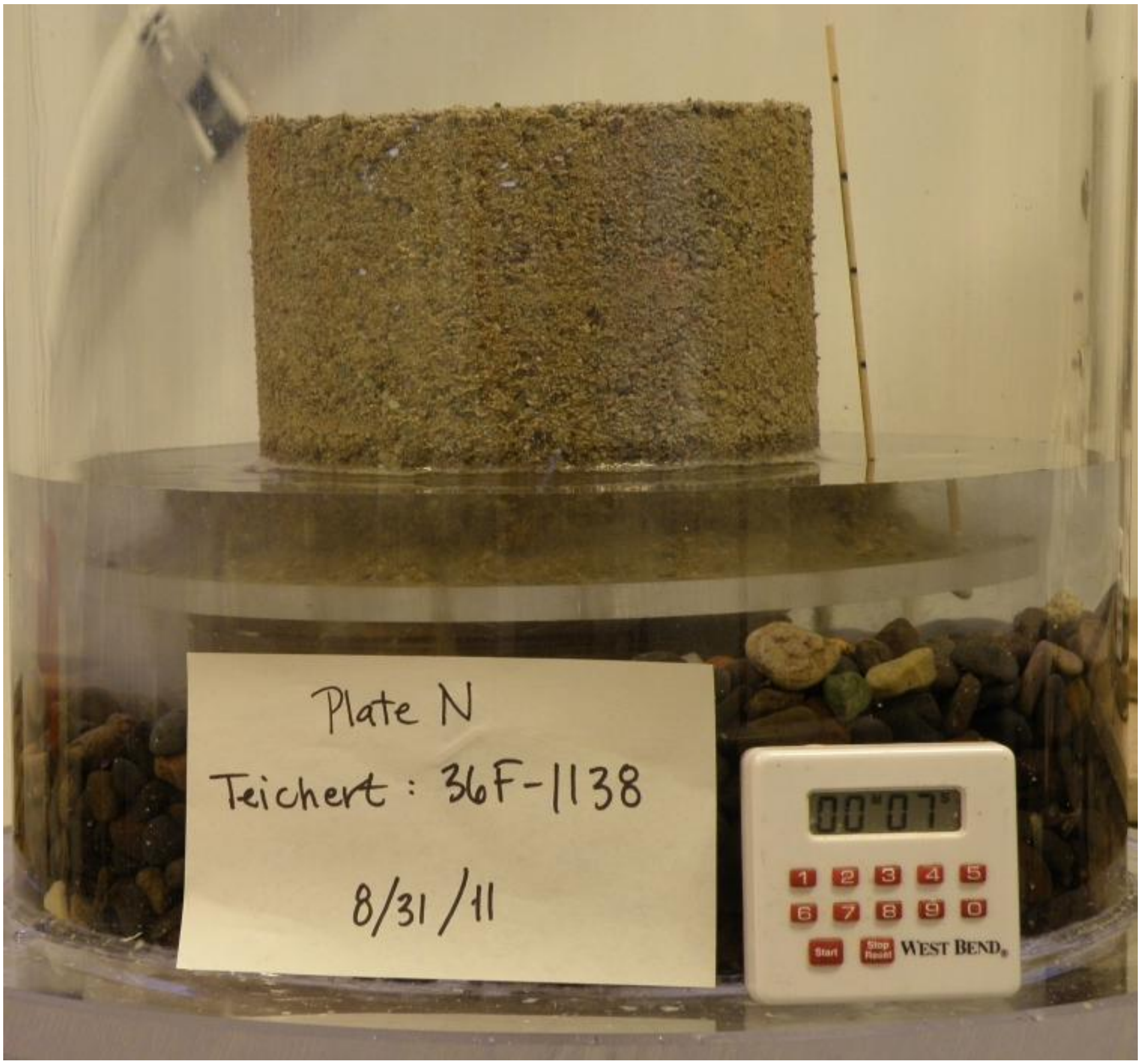


Figure A-10.—Teichert sample at beginning of Sand Castle Test.

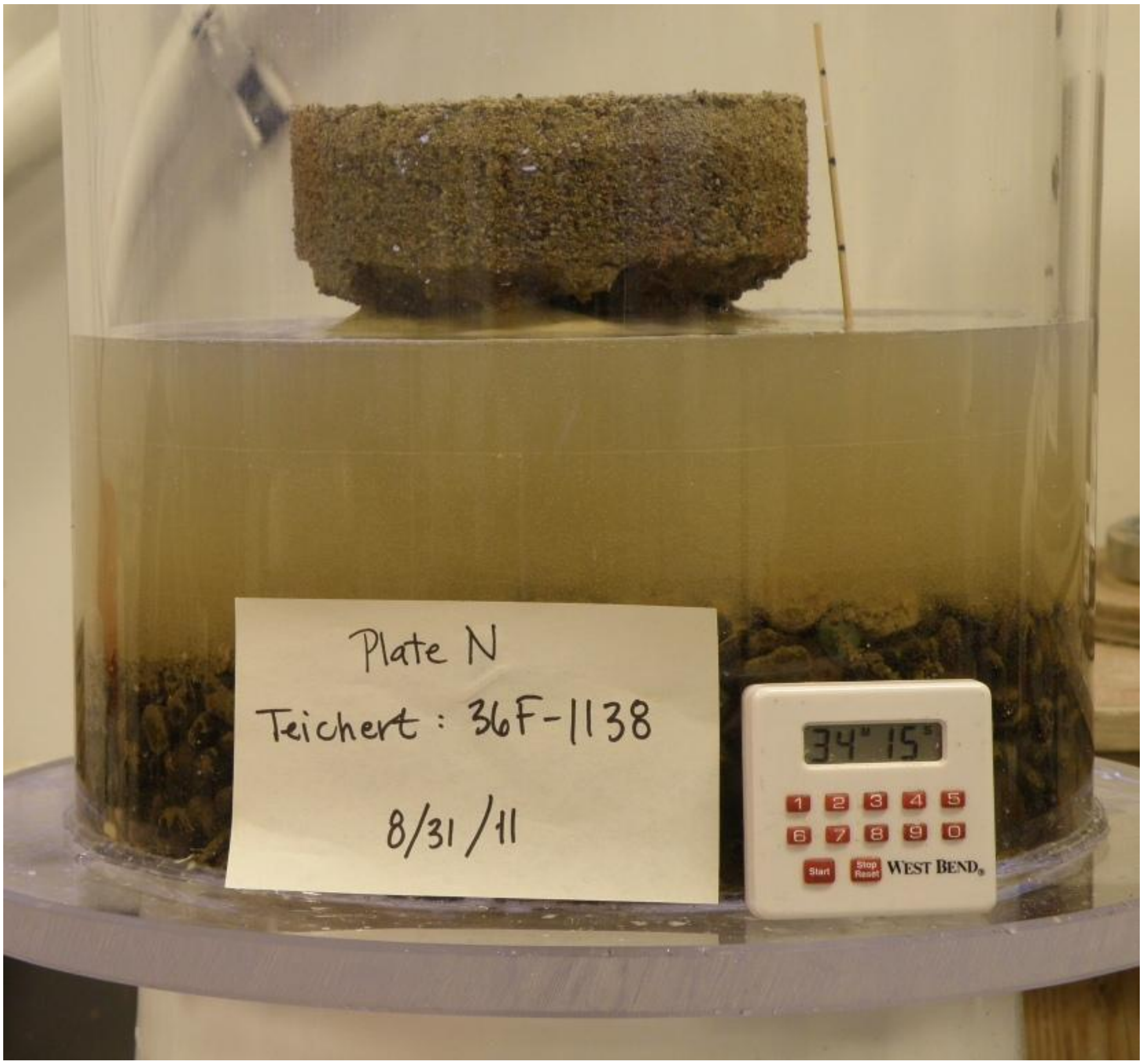


Figure A-11.—Sample shown at 50% disintegration while submerged in 2 inches of water. Notice that sample has yet to reach full absorption at over 34 minutes into the test.

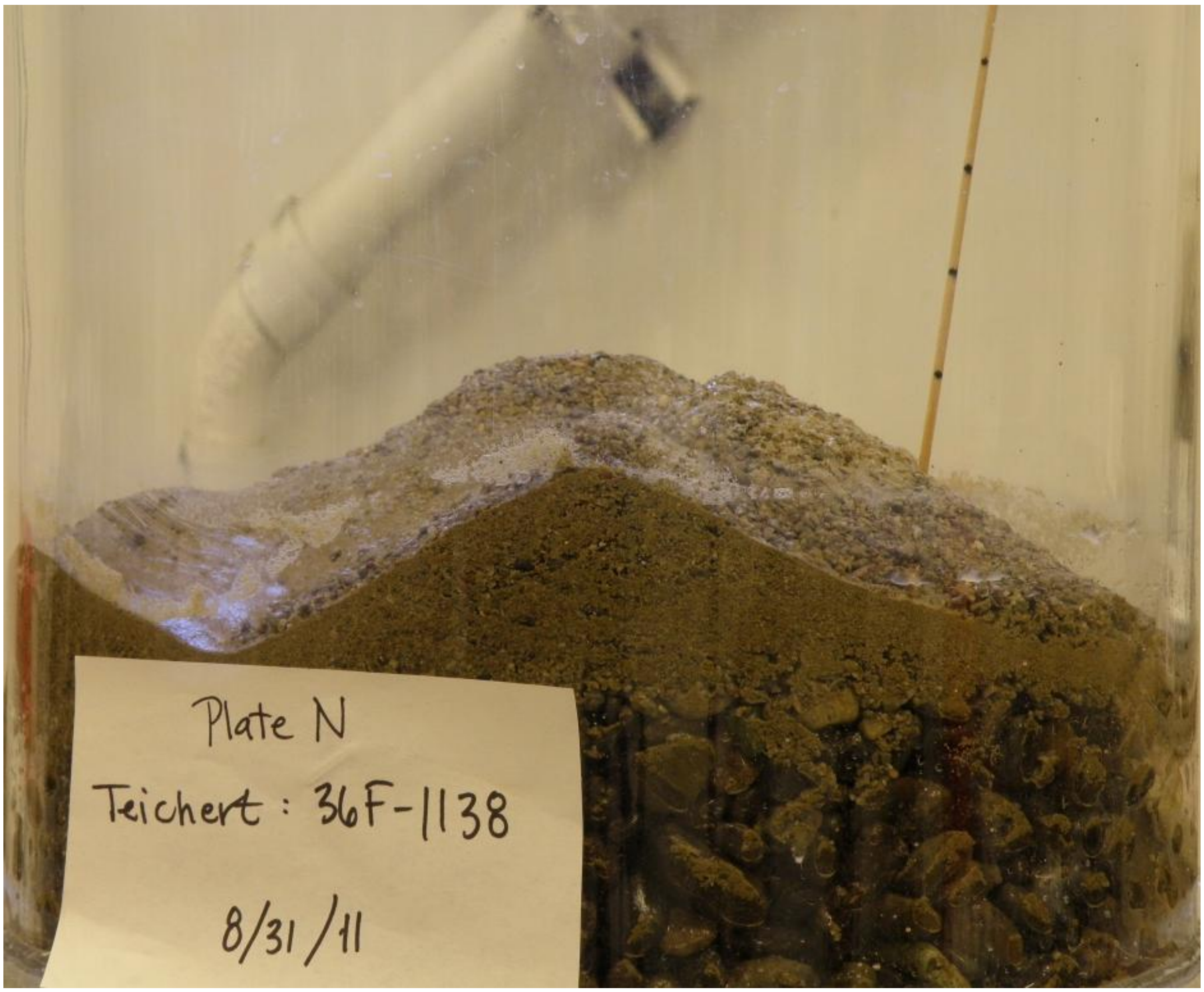


Figure A-12.—Sample at completion of test.

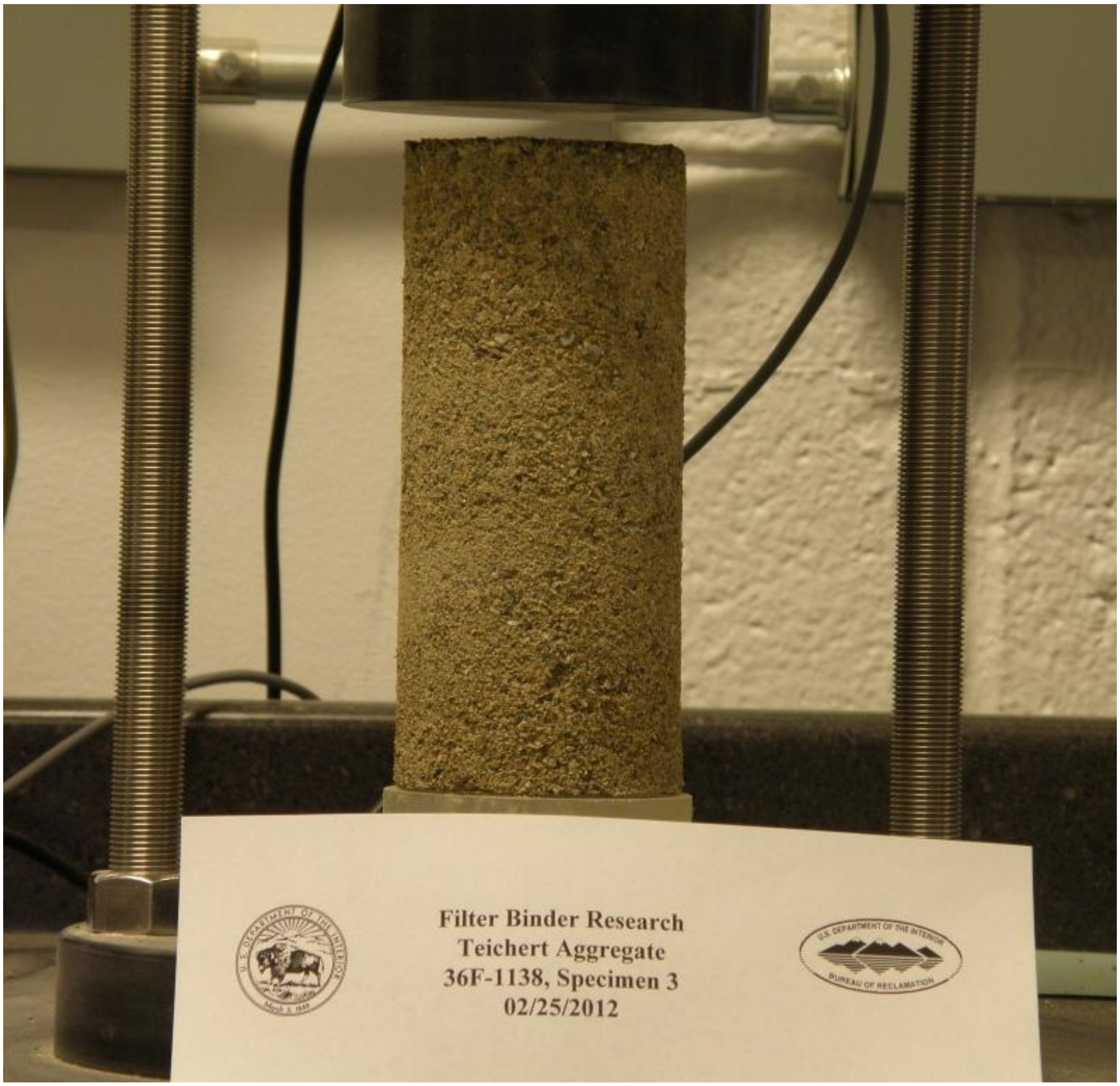


Figure A-13.—Sample before UCS Test.

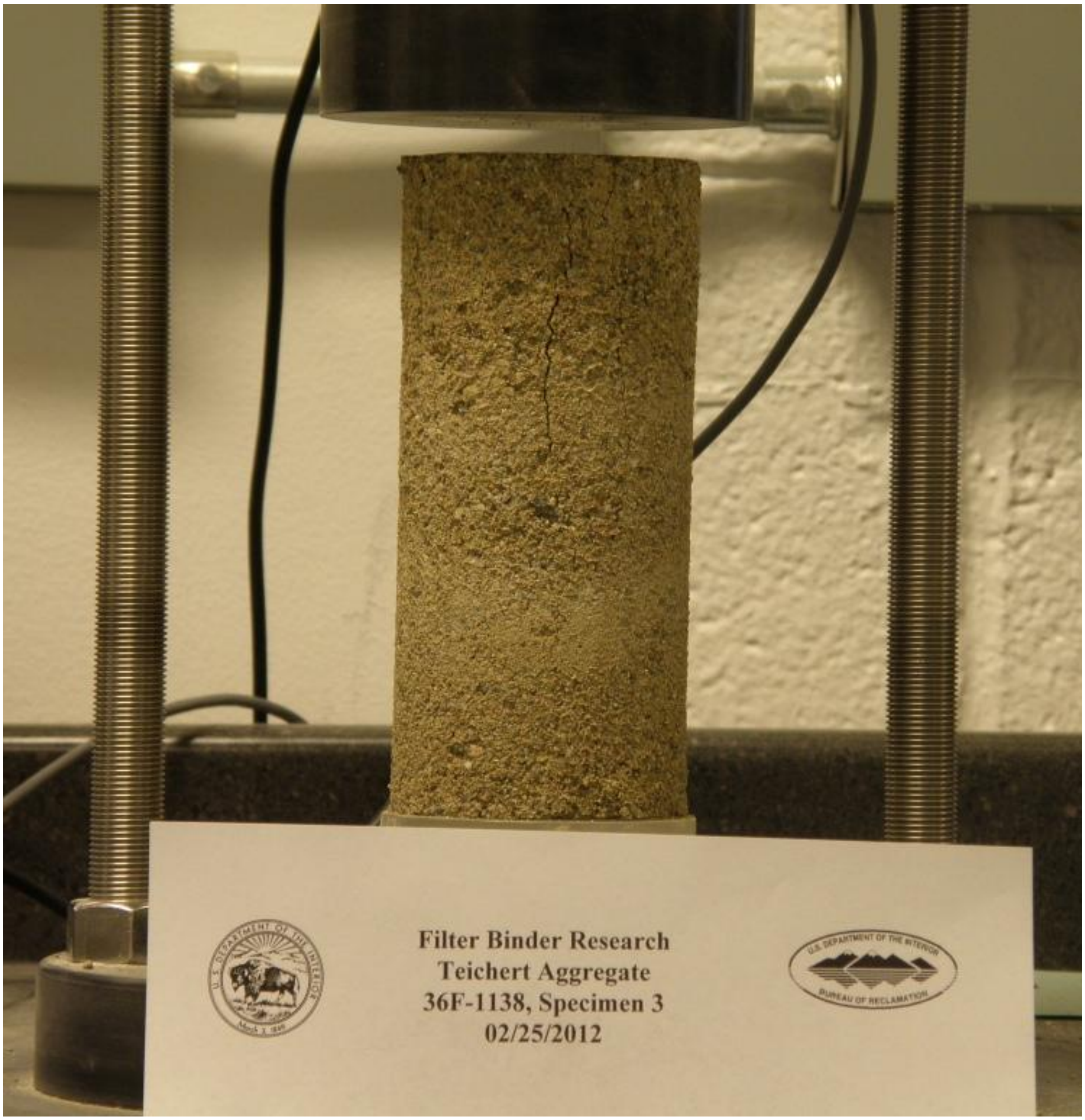


Figure A-14.—Specimen at failure.

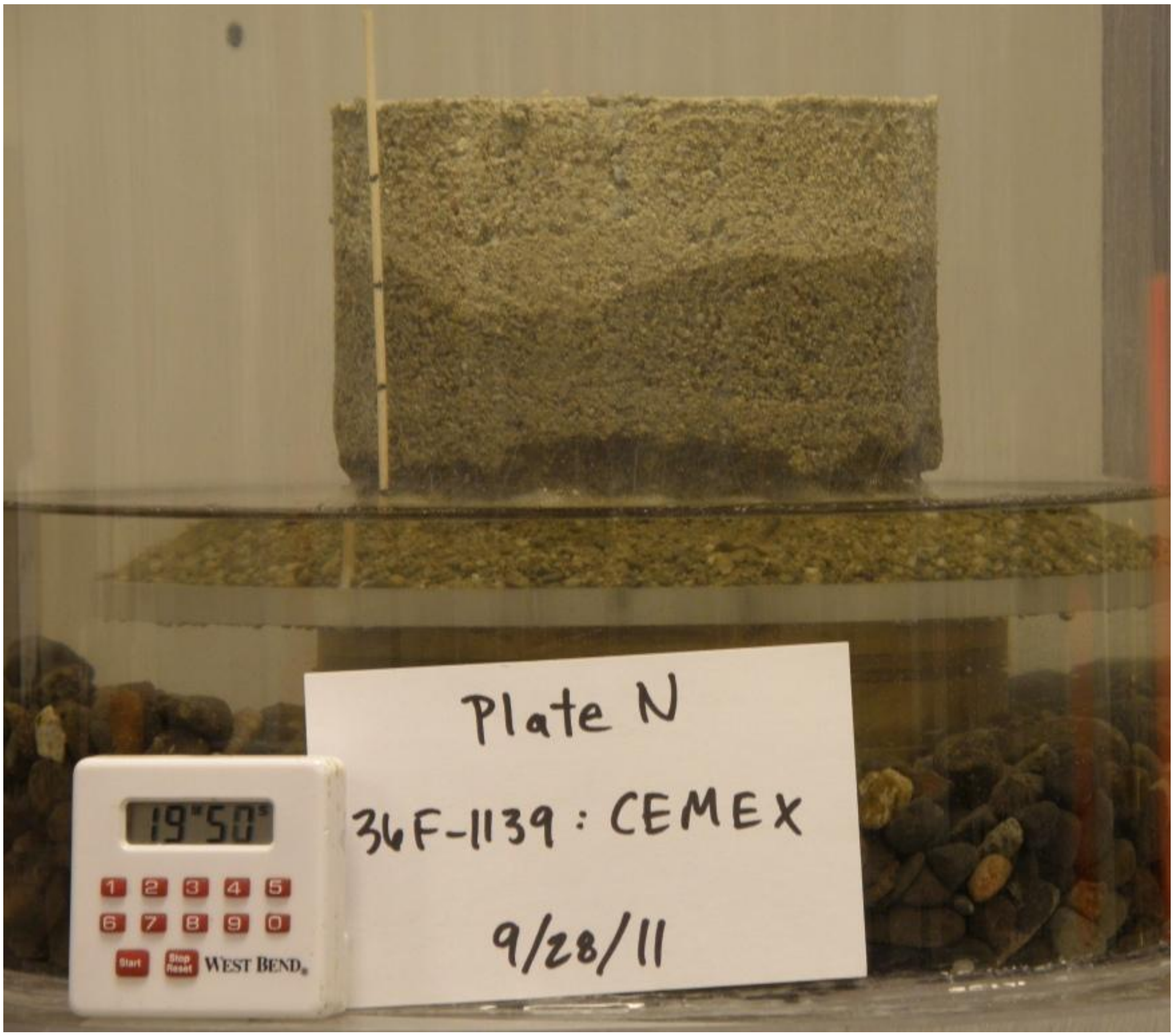


Figure A-15.—Sample during Sand Castle Test. Notice almost 20 minutes has passed and the sample has yet to reach 50% disintegration or full absorption.

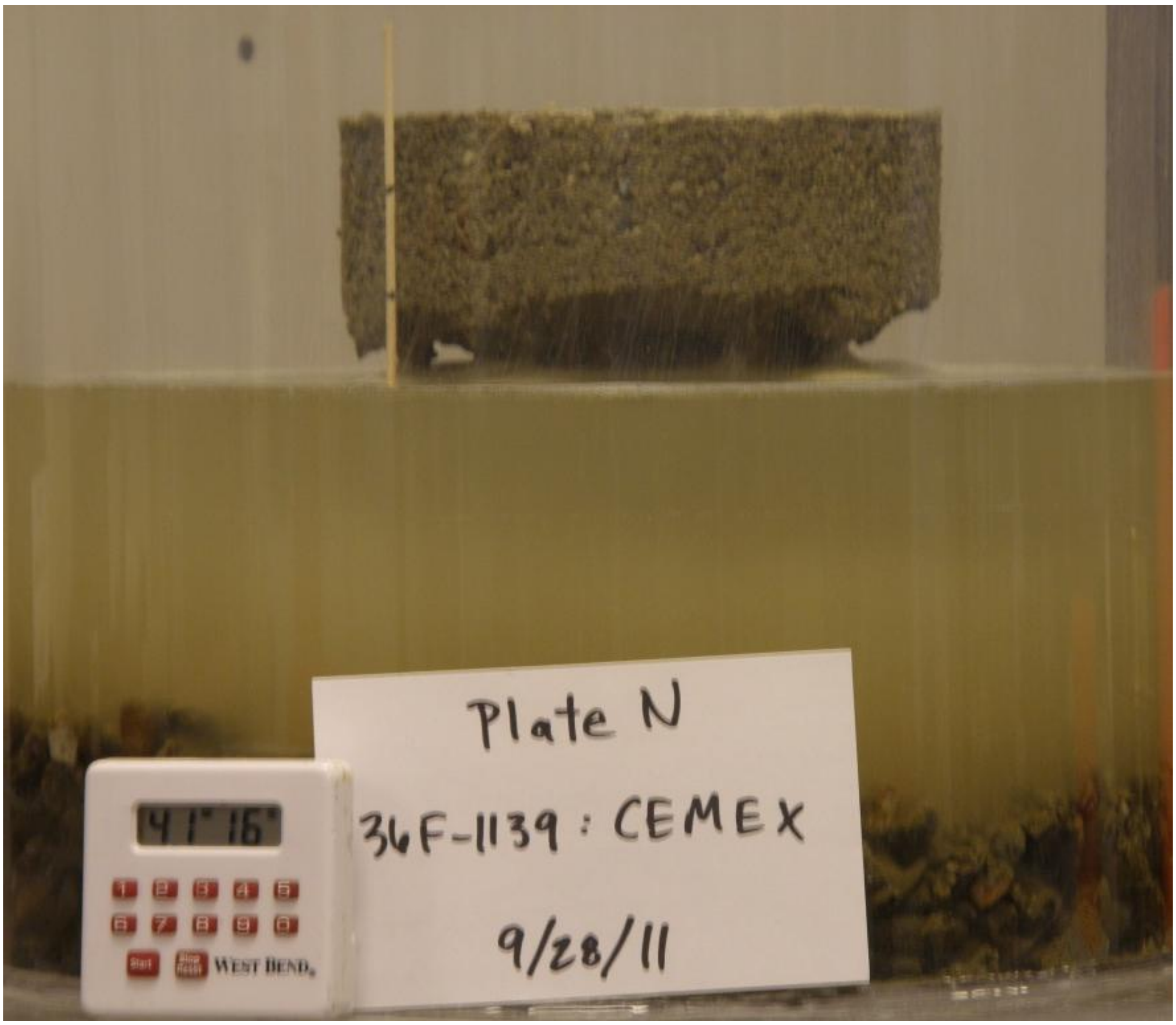


Figure A-16.—Sample shown immediately before failure, having reached full absorption and 50% disintegration.

Figure A-17.—Specimen prior to UCS Test.

Figure A-18.—Speciment at failure.

Figure A-19.—Rotated view of specimen at failure.

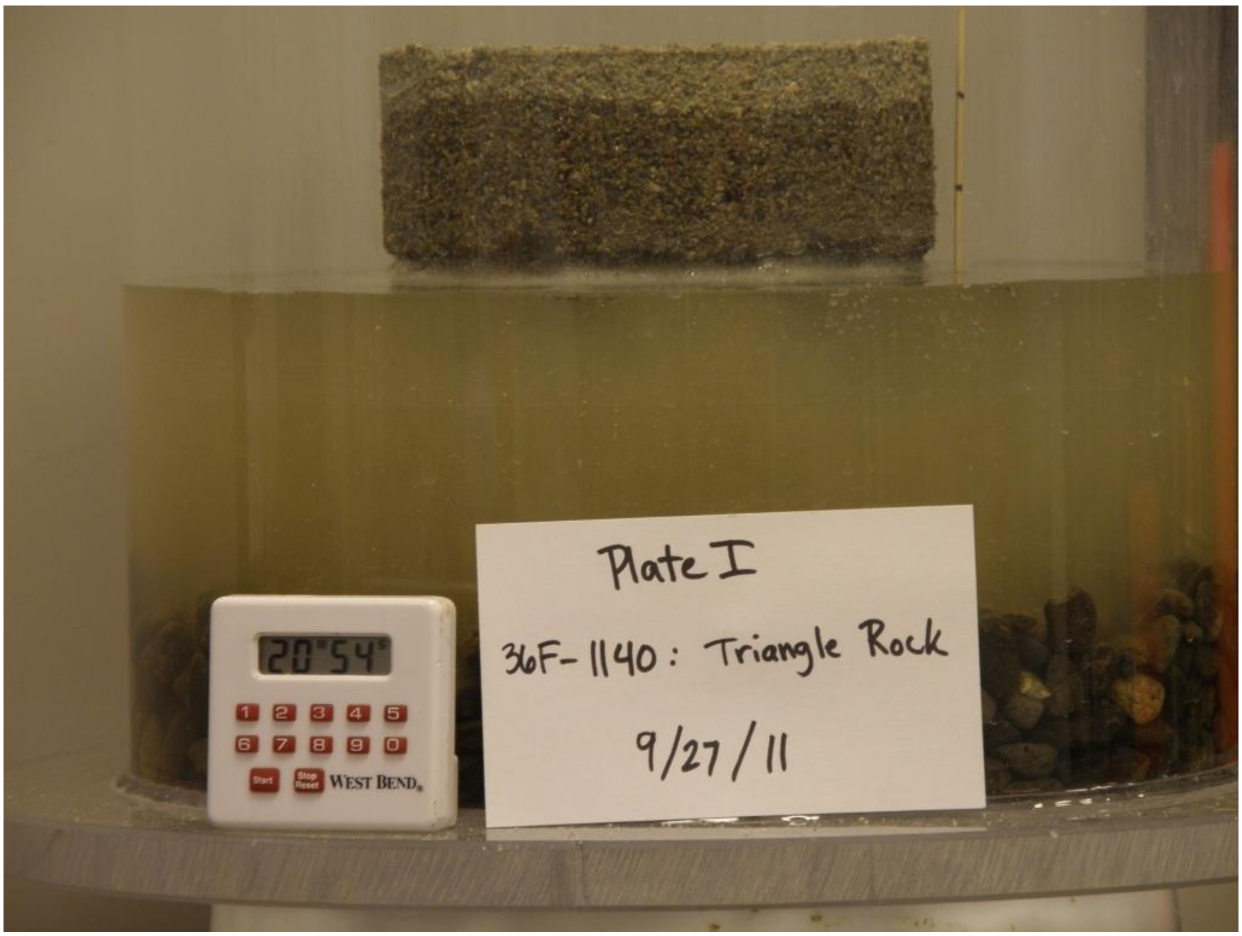


Figure A-20.—Typical sample behavior shown beyond 50% disintegration although the sample has not fully absorbed water.

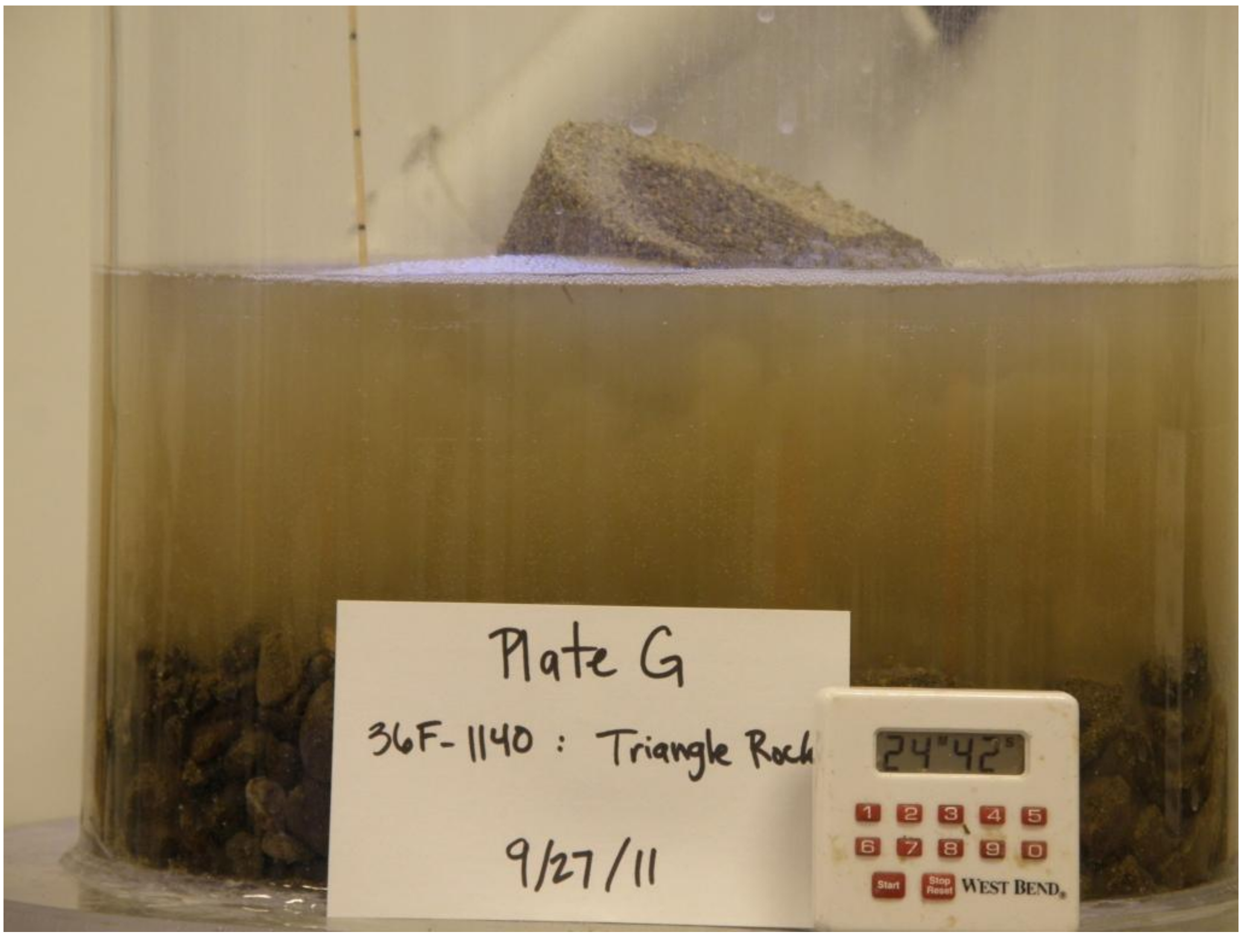


Figure A-21.—Typical "toppling" failure observed of Triangle Rock specimens. Notice sample has *not* reached full absorption.

Figure A-22.—Specimen prior to UCS Test.

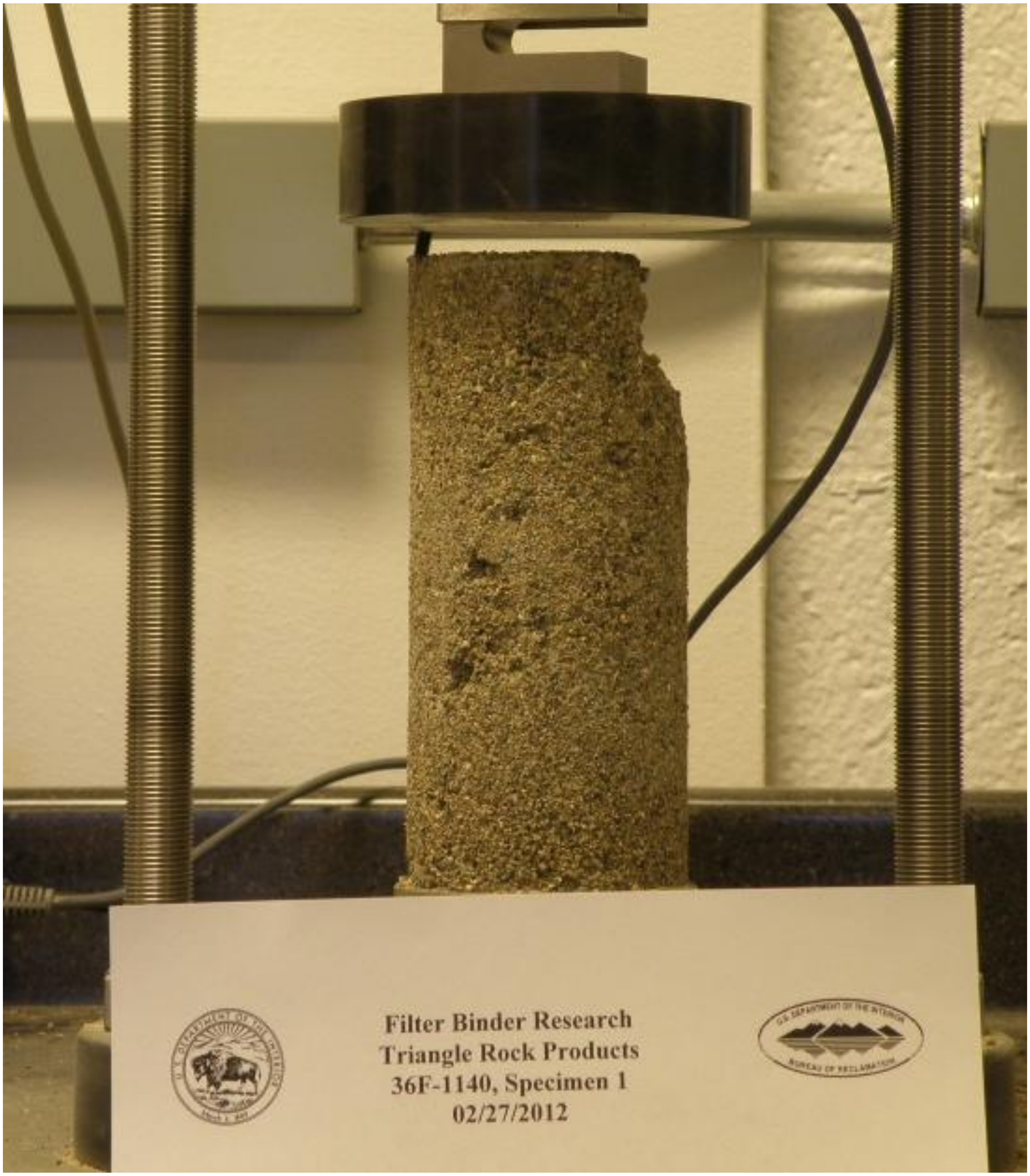


Figure A-23.—Specimen after UCS Test.

Figure A-24.—Granite Rock Sand Castle Test specimen – a typical representation of specimen immediately before failure.

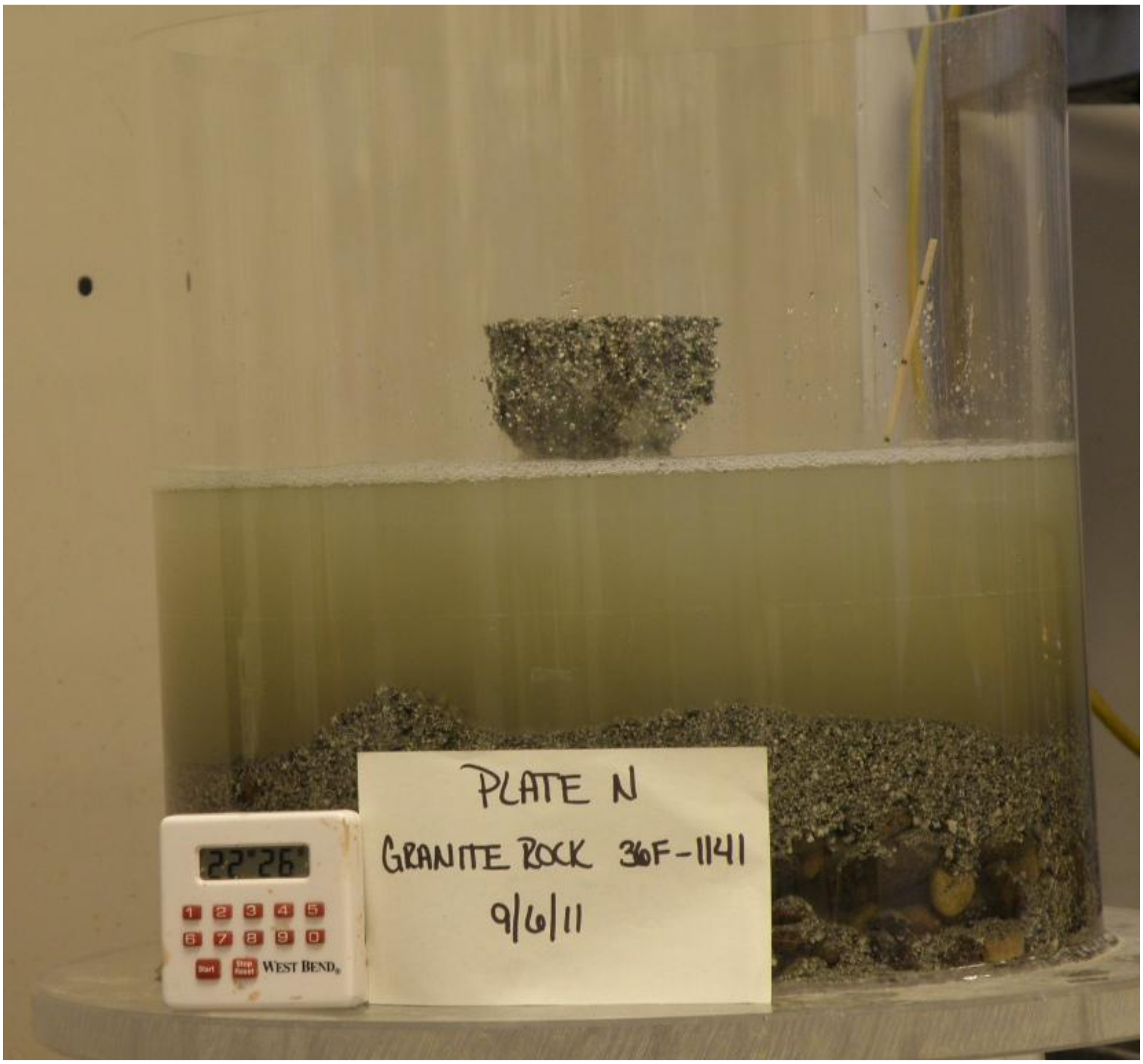


Figure A-25.—A Granite Rock Sand Castle specimen immediately before failure.

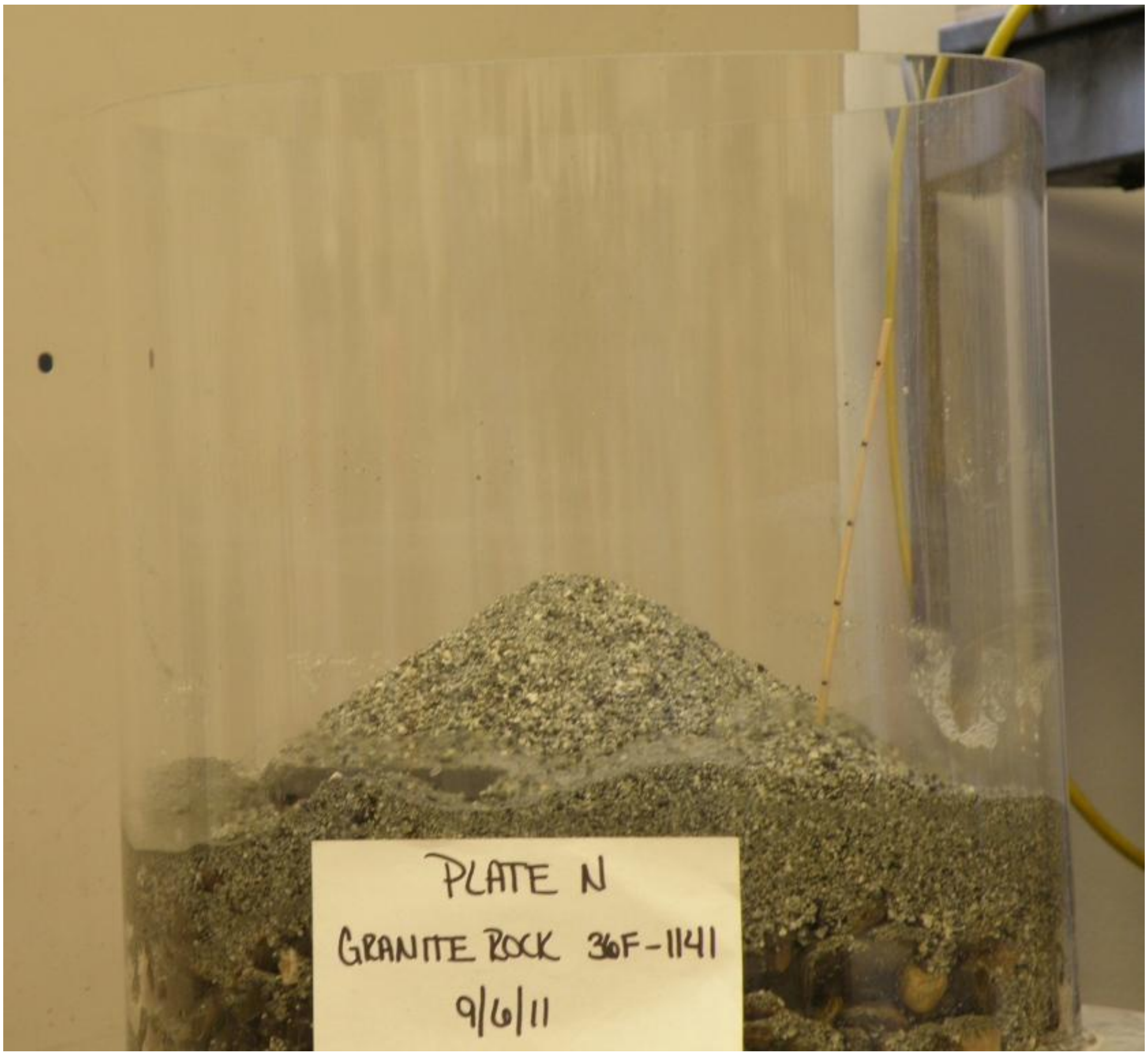


Figure A-26.—Drained sample at completion of Sand Castle Test.

Figure A-27.—Specimen prior to UCS Test.

Figure A-28.—Specimen after UCS Test.

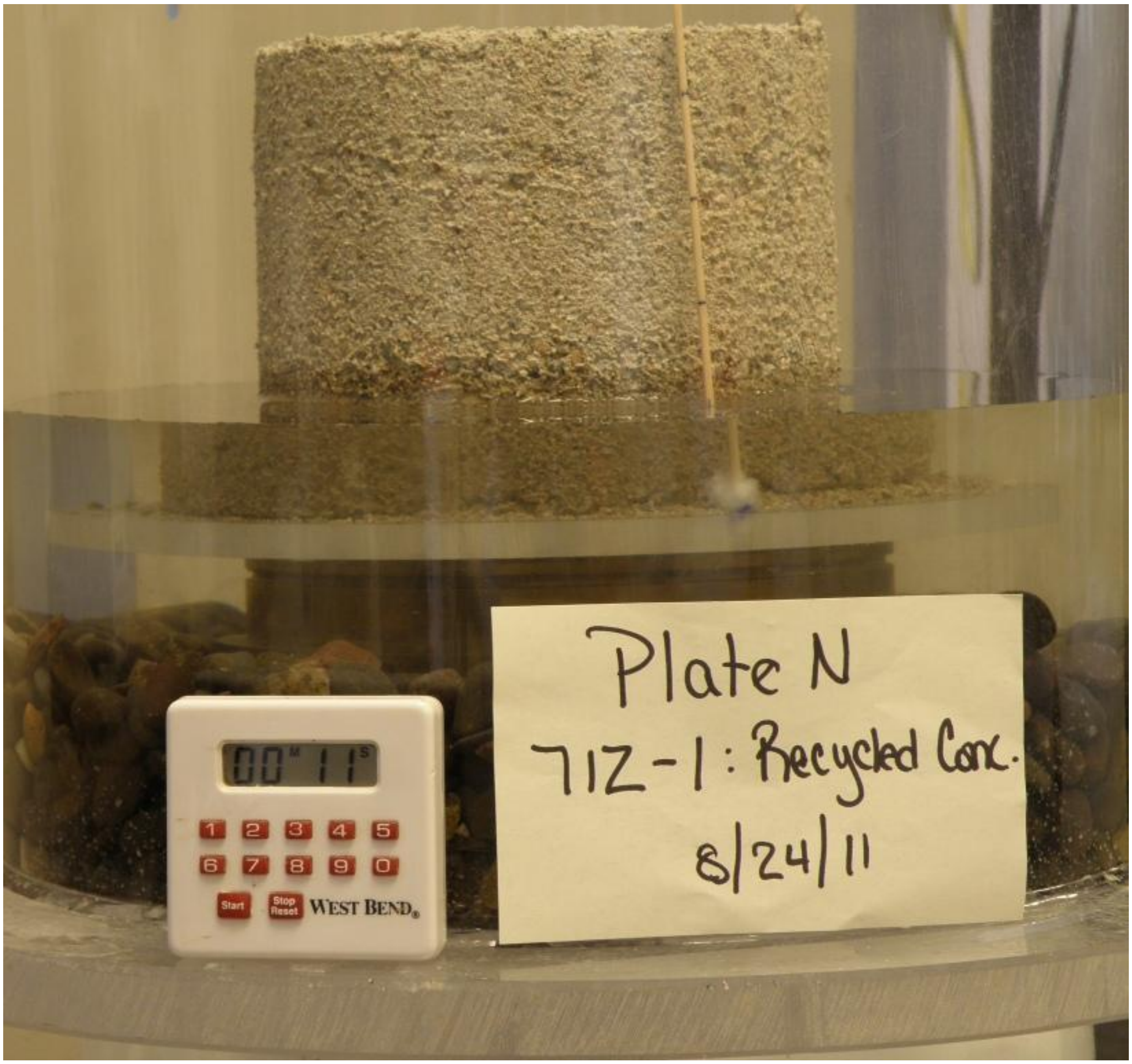


Figure A-29.—Beginning of Sand Castle Test.

Figure A-30.—Specimen shown at over 20 minutes into the test – after the water level was raised to 2 inches.

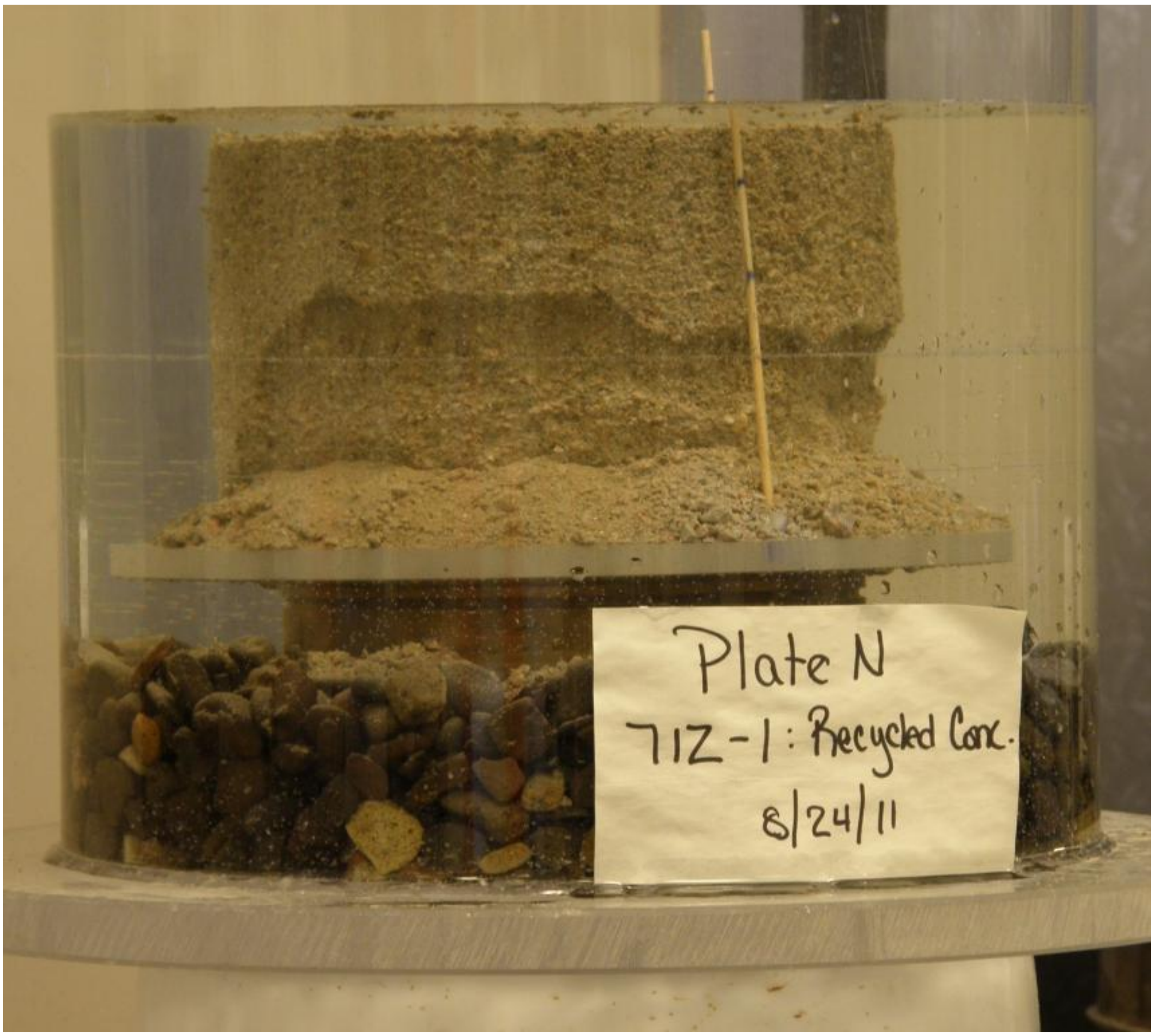


Figure A-31.—Specimen shown completely submerged for over 24 hours. Specimen did not fail during Sand Castle Test.

Figure A-32.—Specimen before UCS Test.

Figure A-33.—Specimen after UCS Test, showing failure.

Figure A-34.—Specimen shown during the beginning of the Sand Castle Test.

Figure A-35.—Specimen at full absorption but not yet 50% disintegration.

Figure A-36.—Sample shown just before failure.

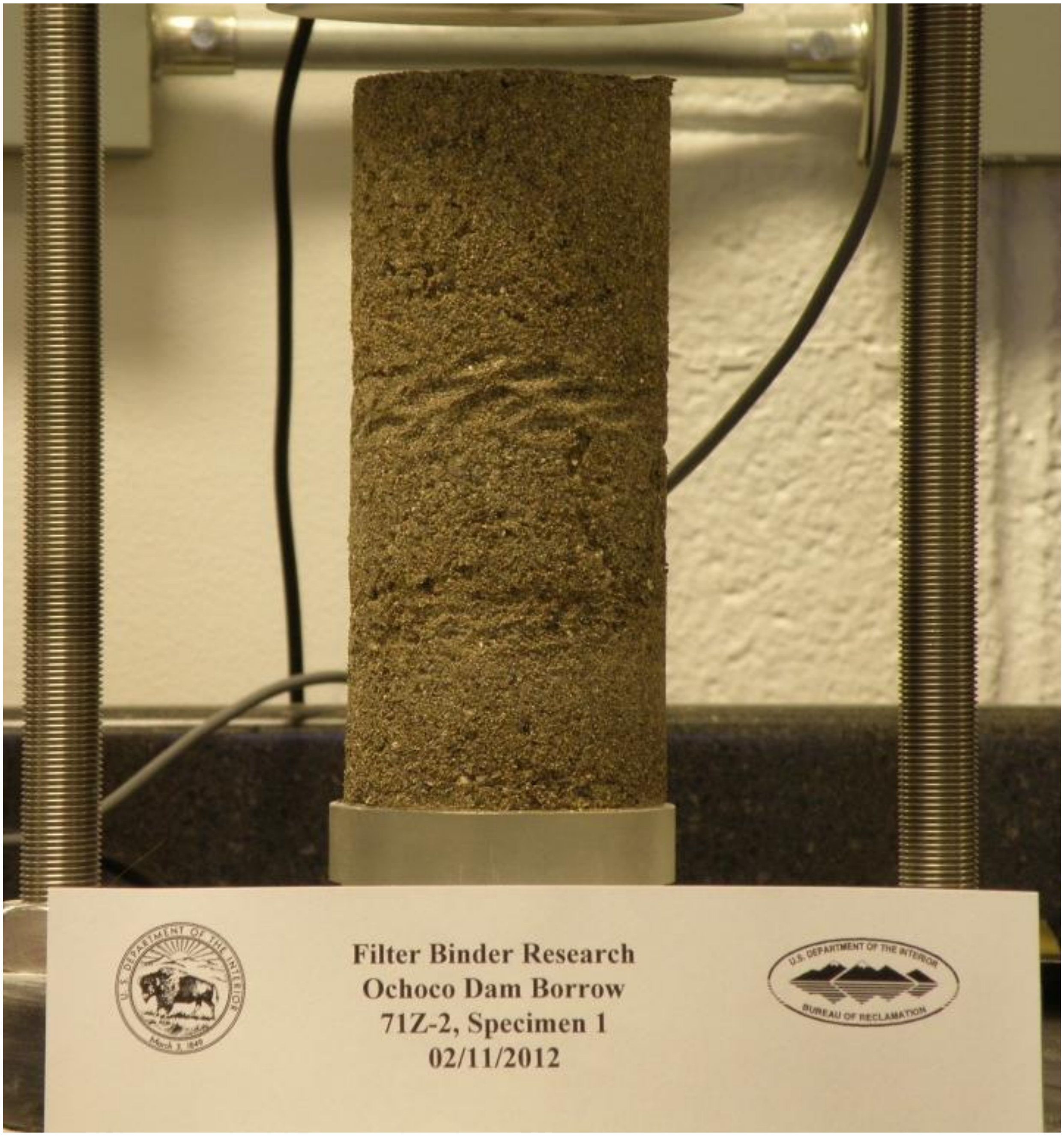


Figure A-37.—Sample shown before UCS Test.

Figure A-38.—Specimen after UCS Test.

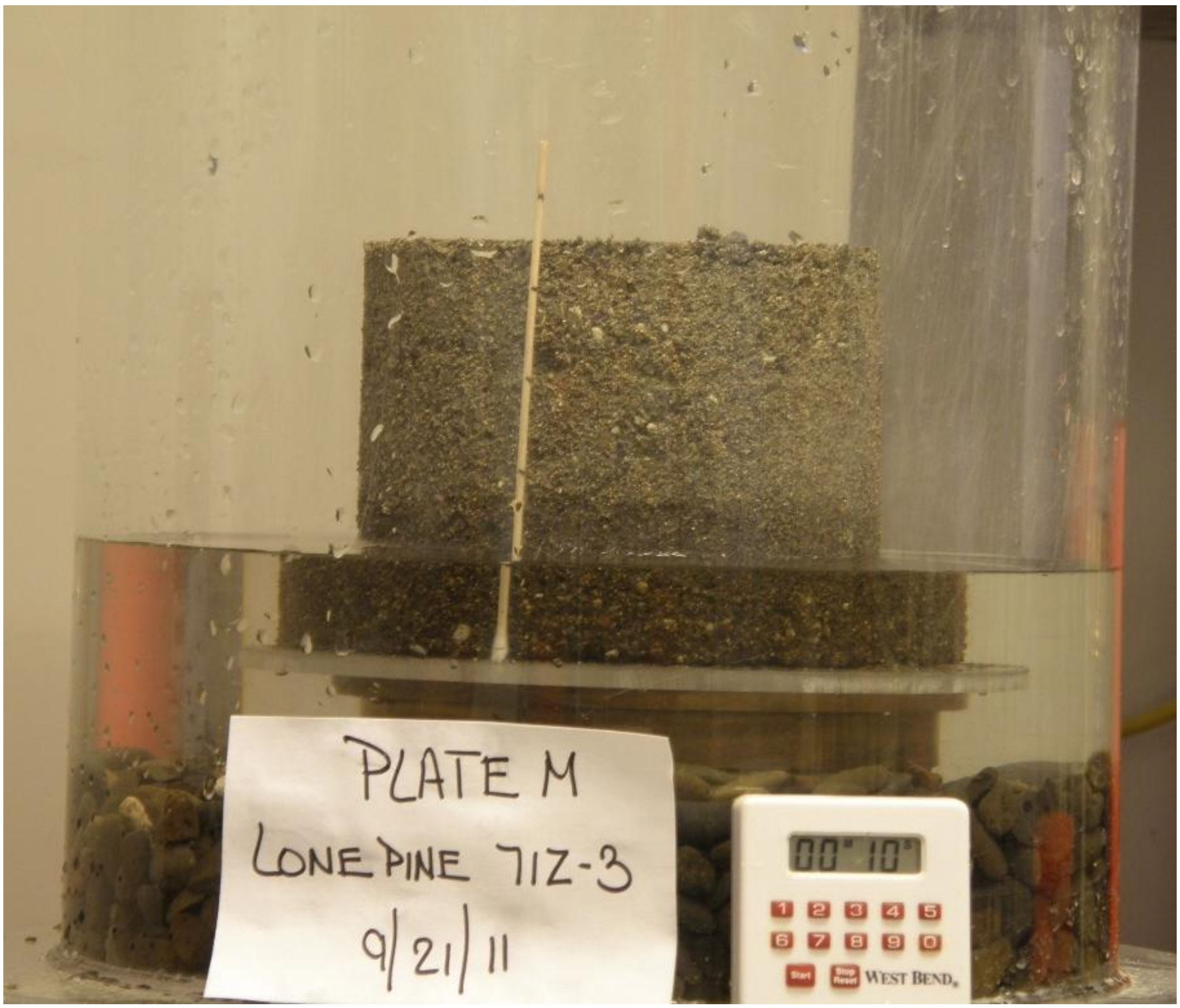


Figure A-39.—Sample shown at start of Sand Castle Test.

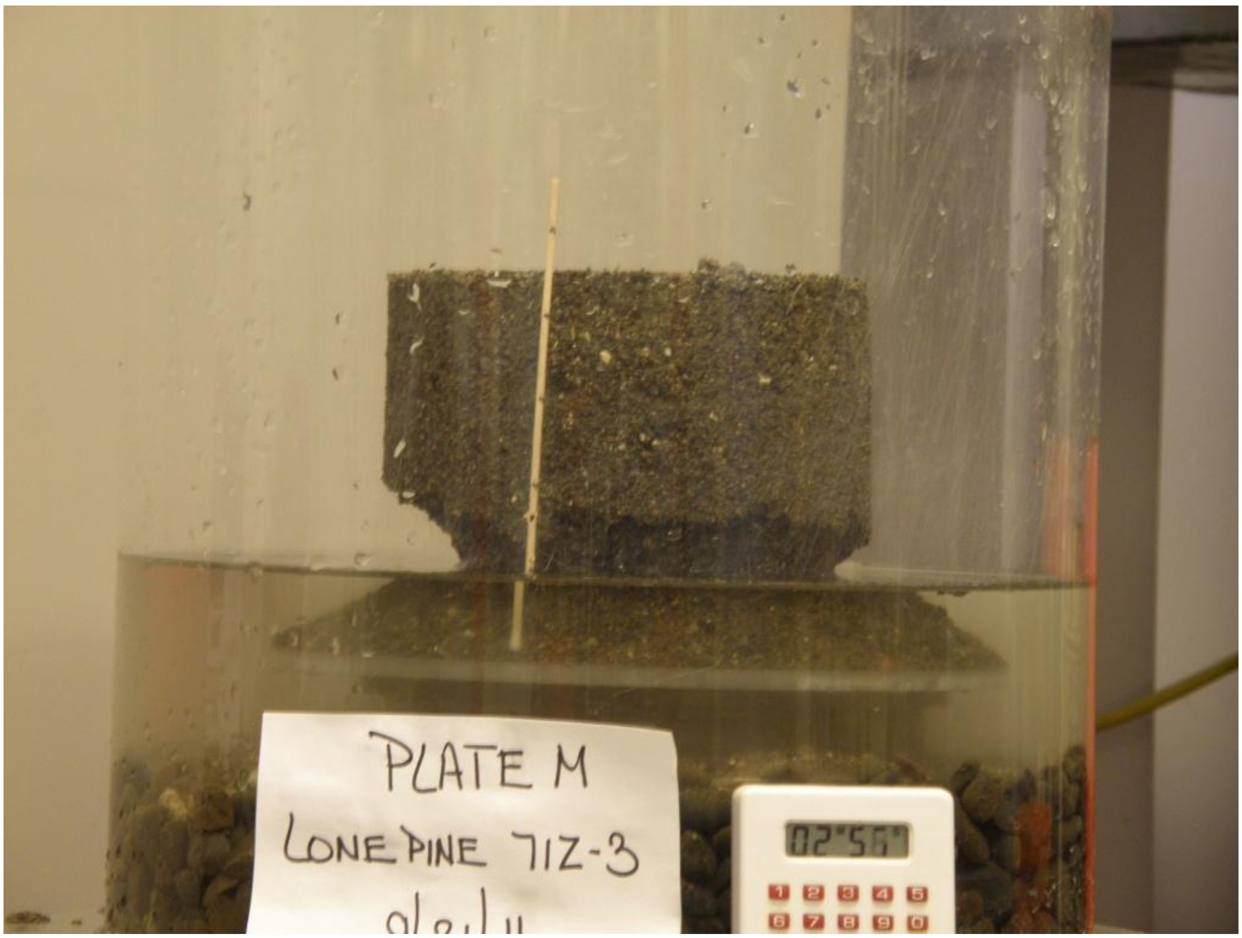


Figure A-40.—Specimen has fully absorbed water.

Figure A-41.—Typical "topple" failure.

Figure A-42.—Specimen before UCS Test.

Figure A-43.—Specimen after UCS Test.

Figure A-44.—Specimen has almost fully absorbed water.

Figure A-45.—Specimen at 50% disintegration after water raised to 2 inches.

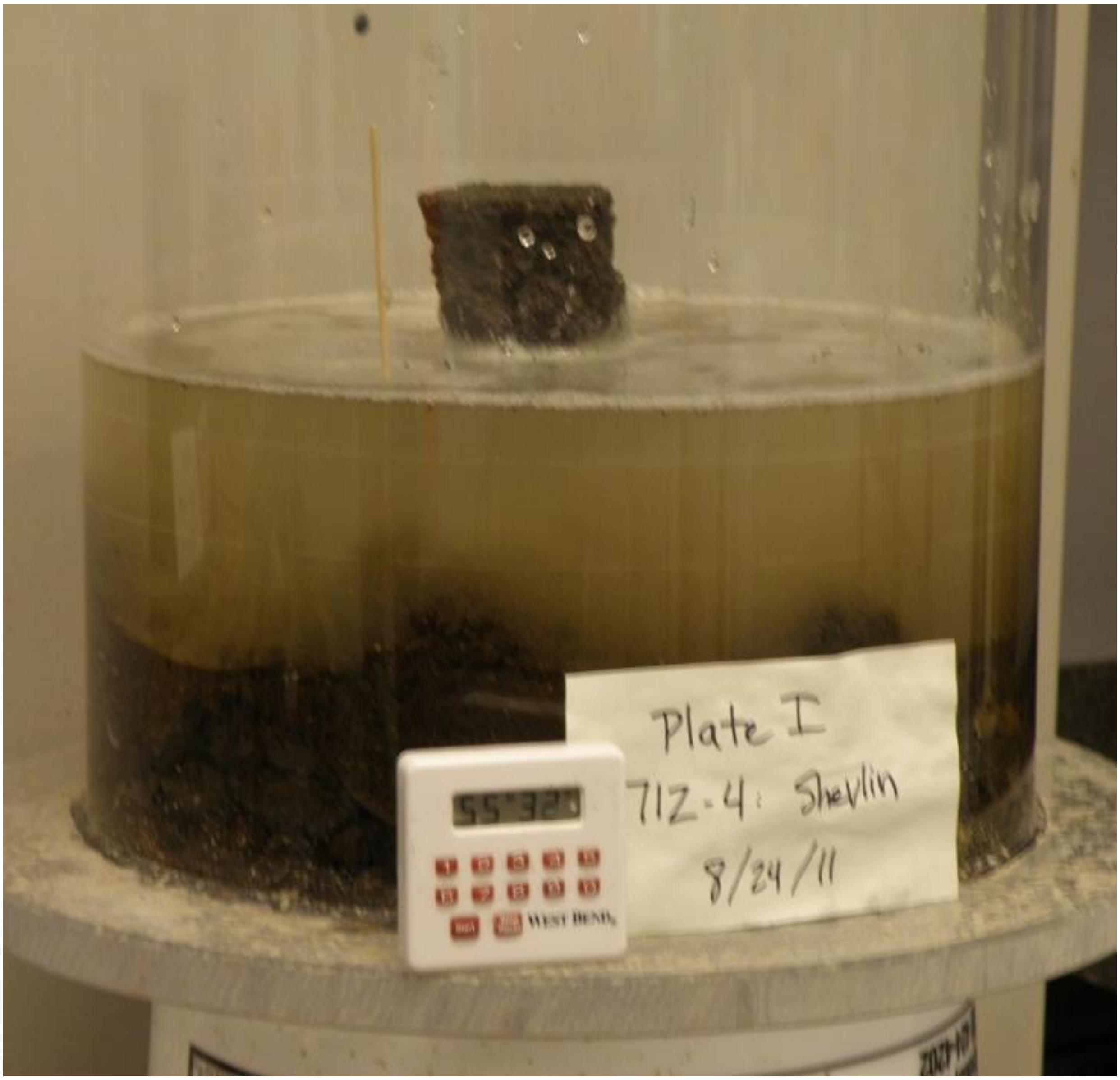


Figure A-46.—Typical specimen immediately before failure.

Figure A-47.—Specimen before UCS Test.

Figure A-48.—Specimen after UCS Test, showing failure.

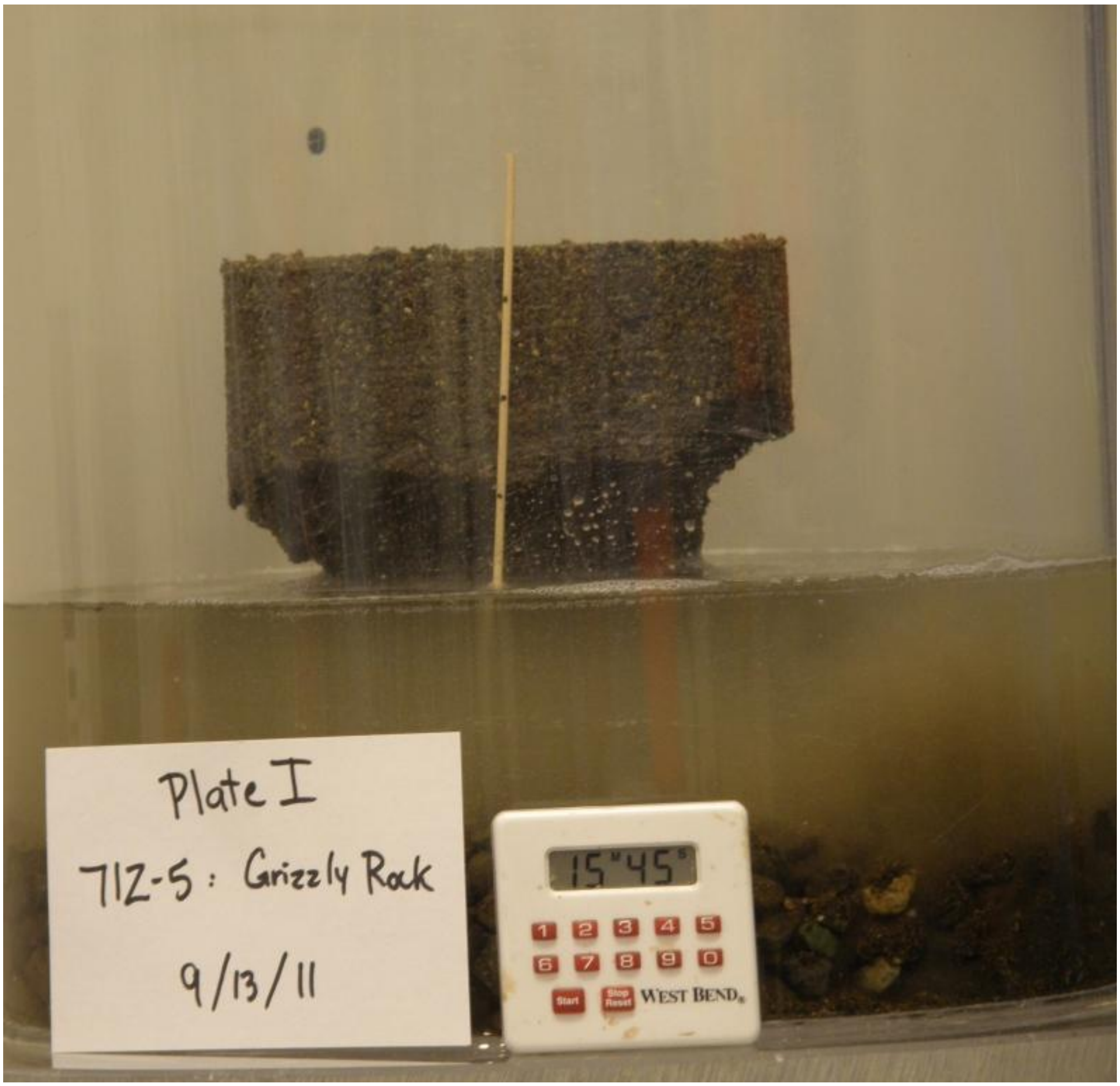


Figure A-49.—Typical specimen prior to failure.

Figure A-50.—Typical specimen “topple” failure.

Figure A-51.—Grizzly rock specimen before UCS Test.

Figure A-52.—Specimen after failure.

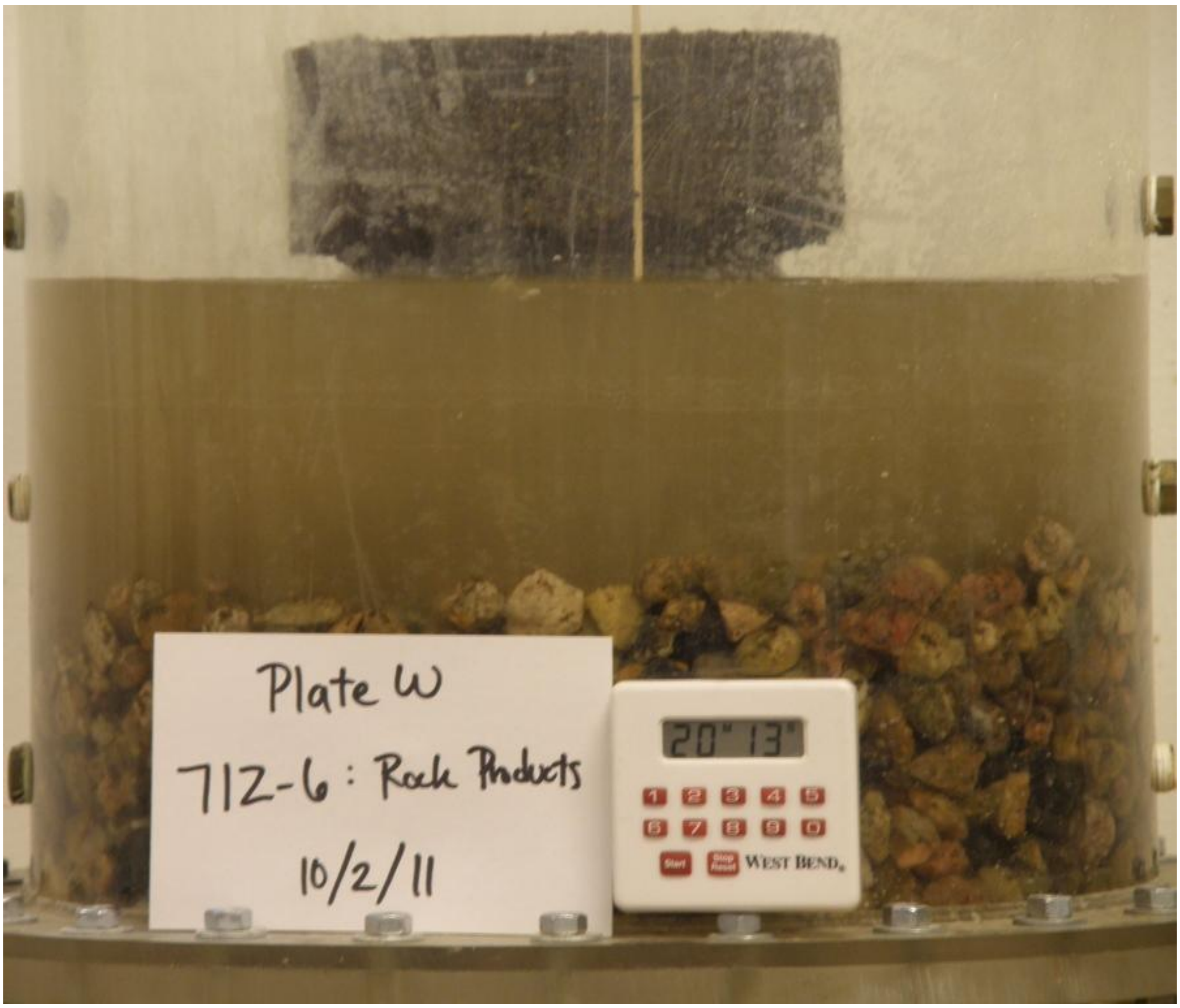


Figure A-53.—Specimen showing full absorption and 50% disintegration.

Figure A-54.—Shows specimen immediately after failure.

Figure A-55.—Specimen before UCS Test.

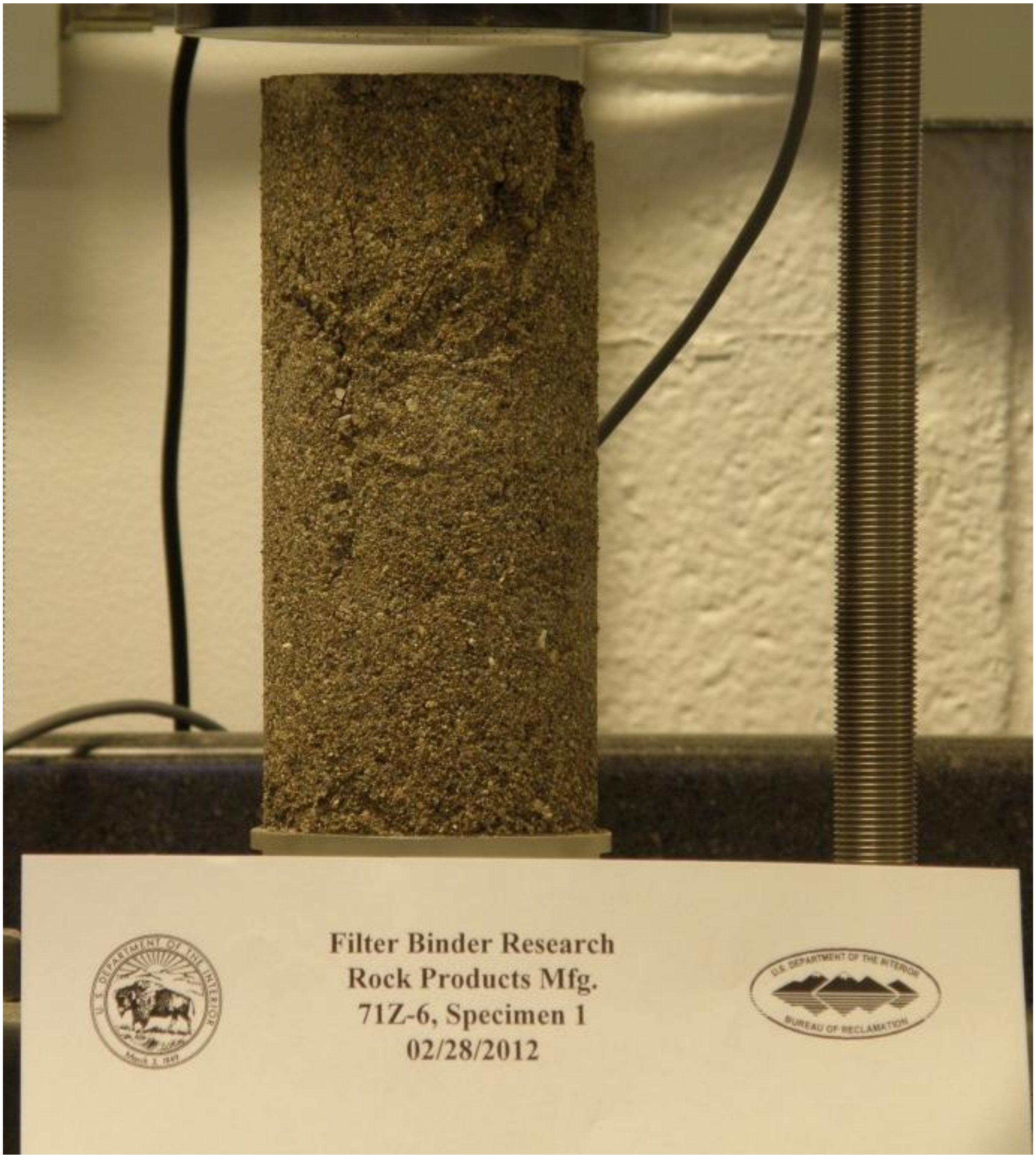


Figure A-56.—Specimen after UCS Test.

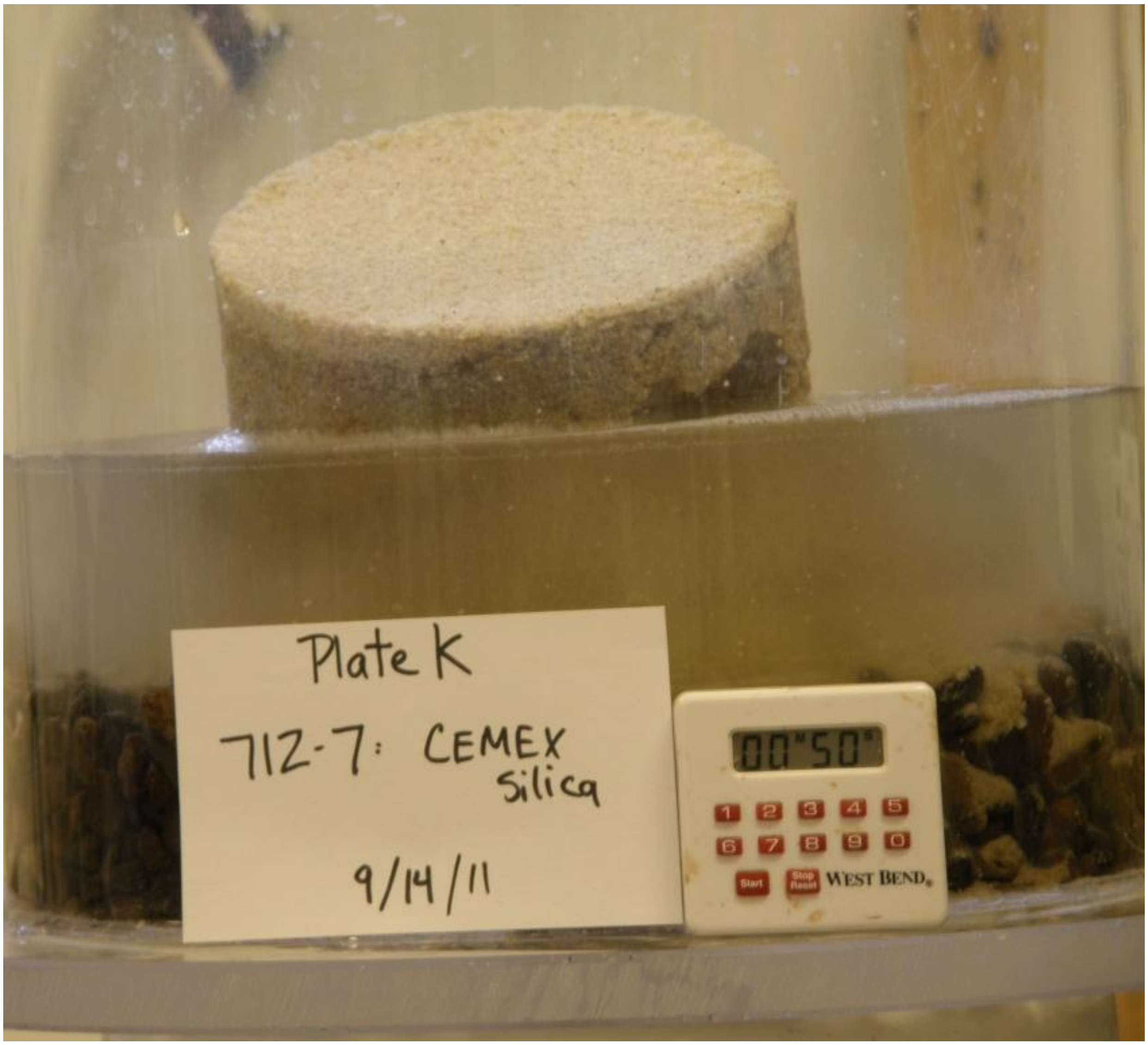


Figure A-57.—Typical Cemex Silica specimen “topple” failure.

Figure A-58.—Another Cemex “topple” failure.

Figure A-59.—Cemex specimen before UCS Test.

Figure A-60.—Cemex sample after UCS Test.

Figure A-61.—Florida Cemex specimen at beginning of Sand Castle Test.

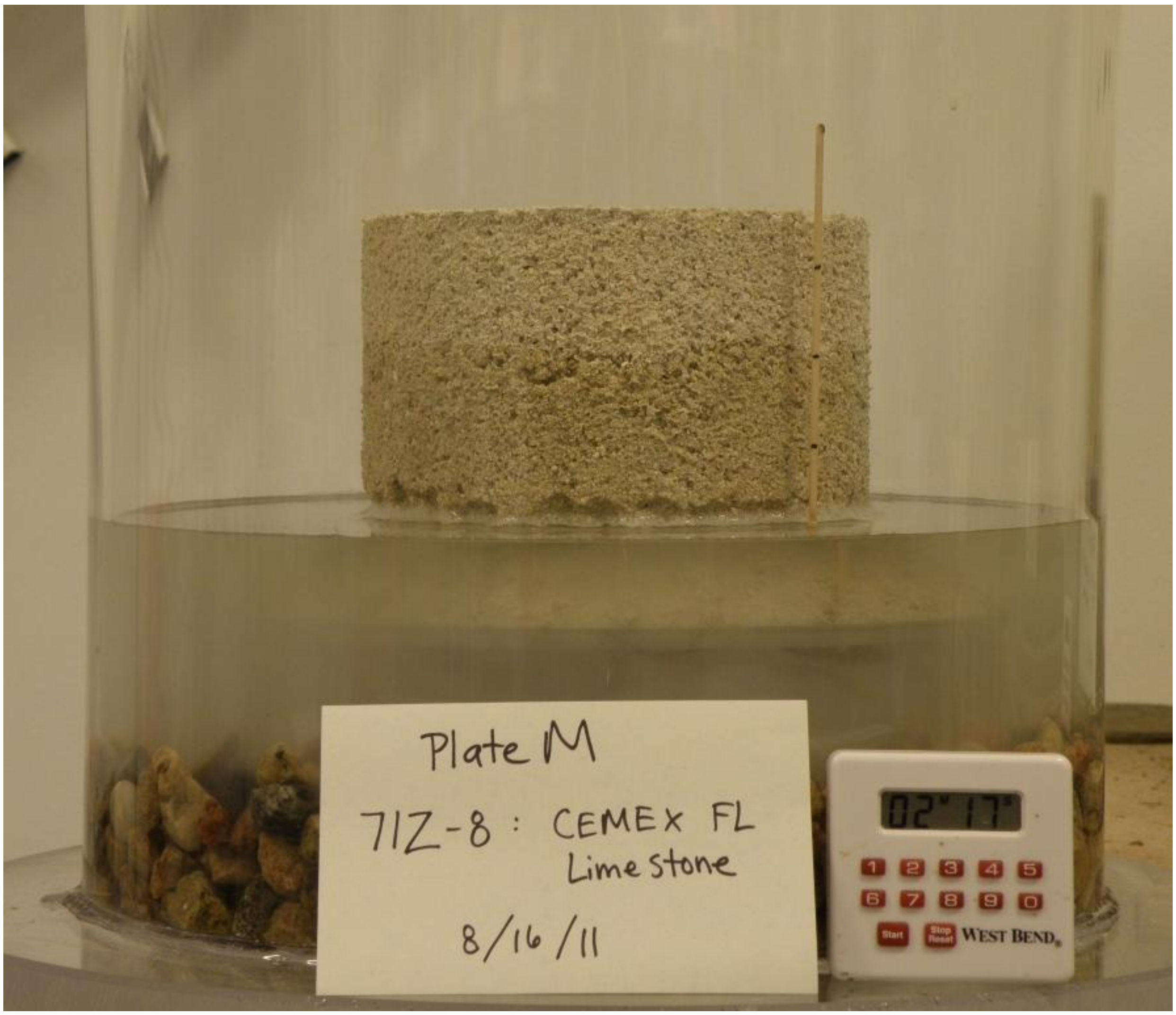


Figure A-62.—Typical Florida Cemex sample absorbing water.

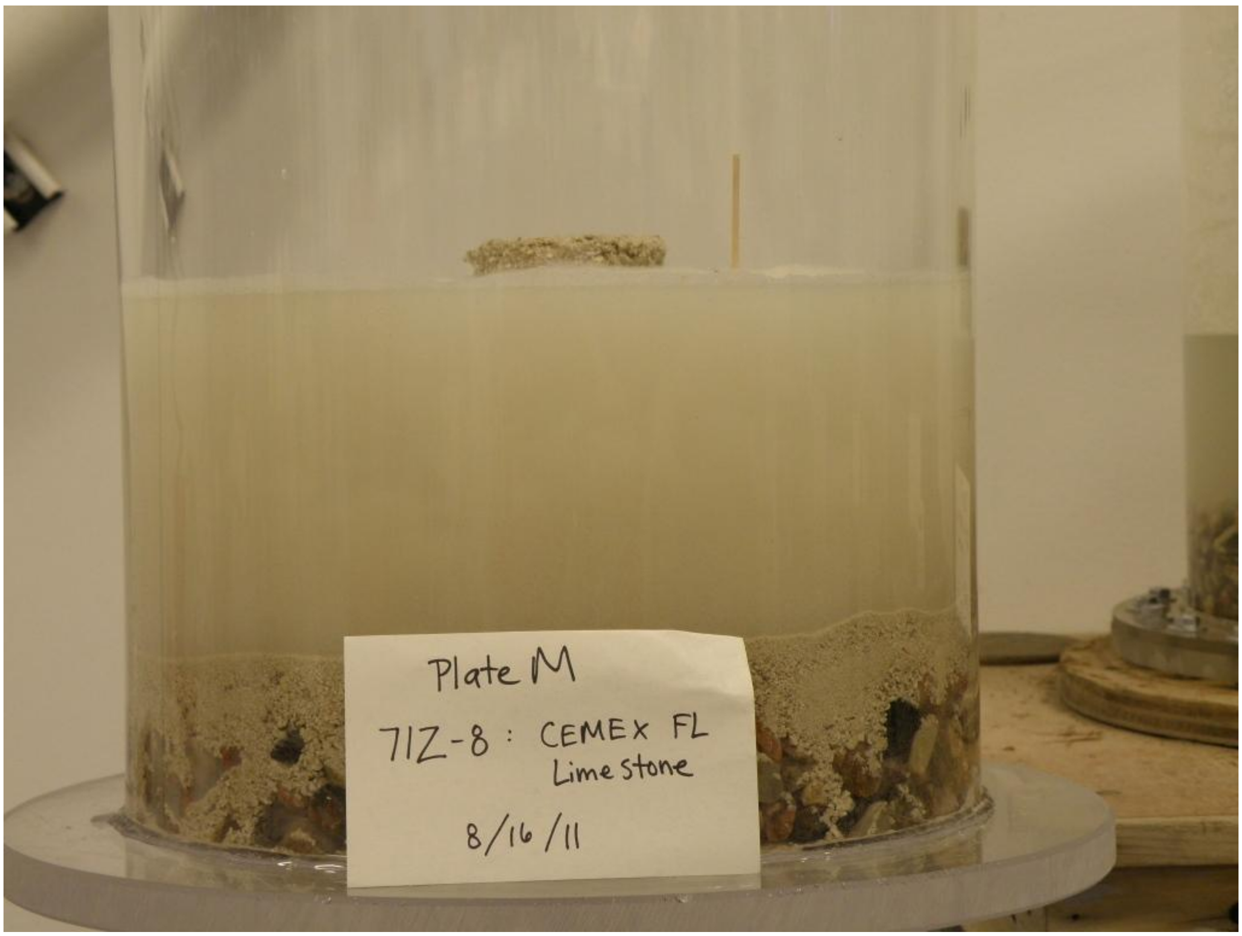


Figure A-63.—Specimen at failure.

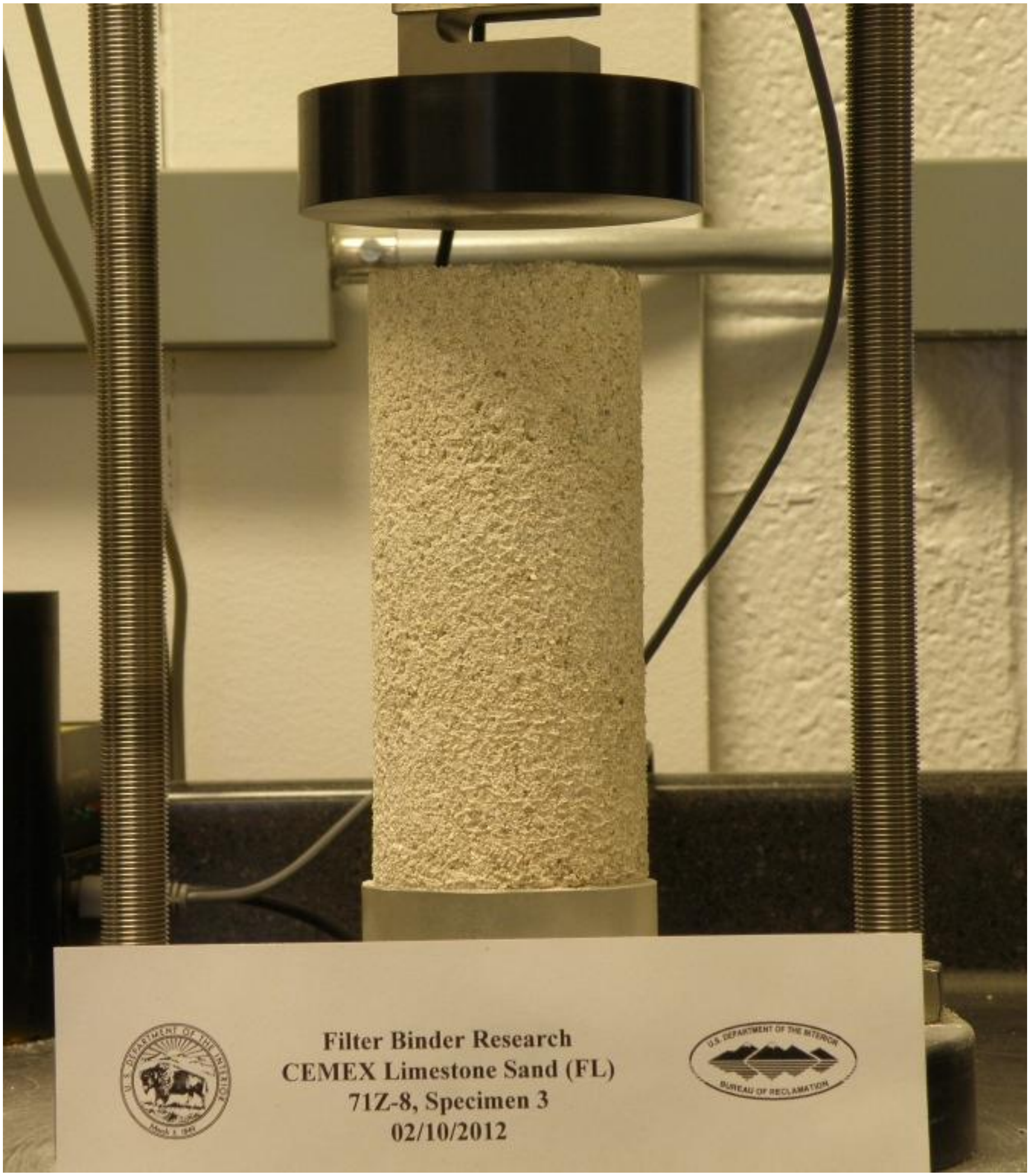


Figure A-64.—Specimen before UCS Test.

Figure A-65.—Specimen at failure.

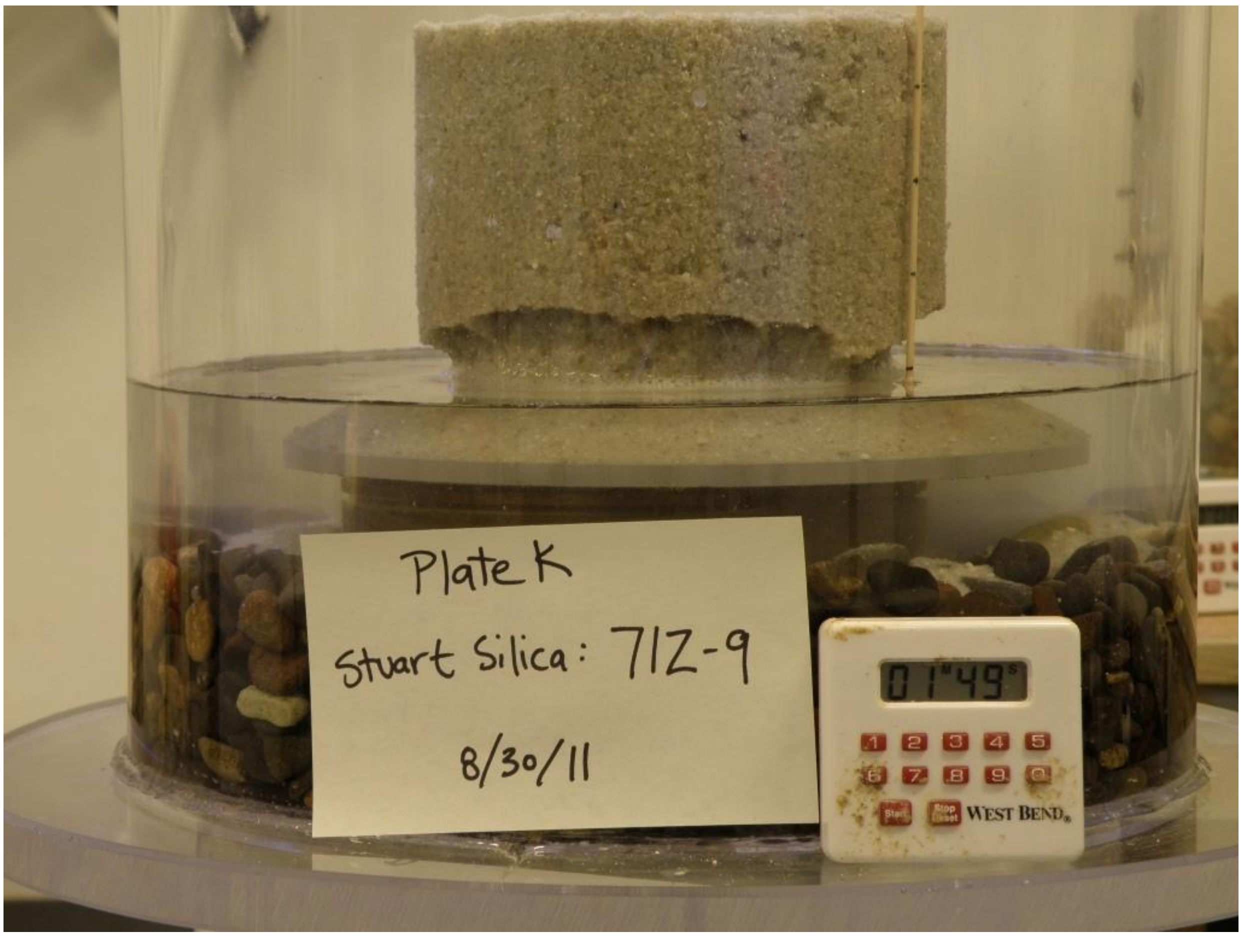


Figure A-66.—Specimen at full absorption.

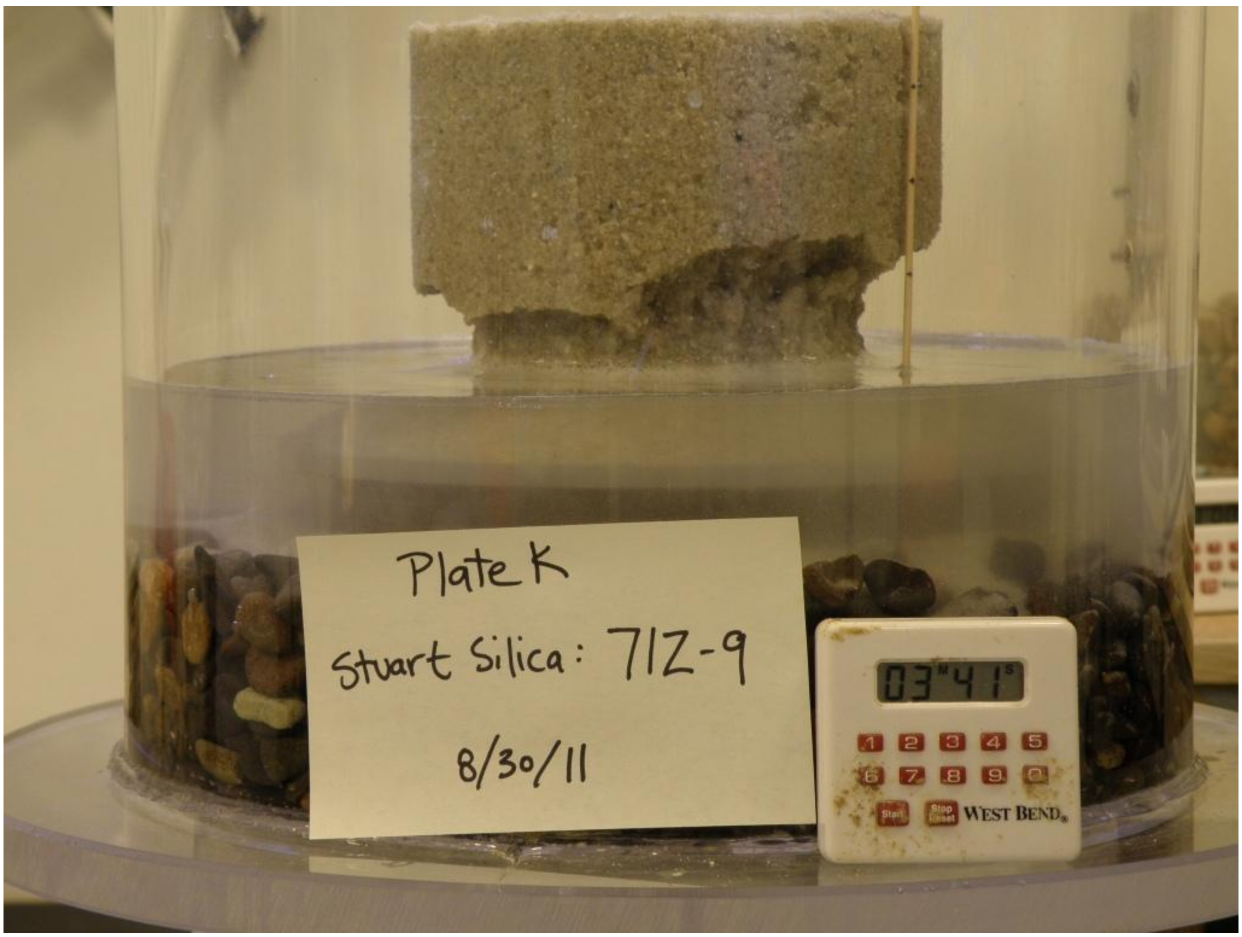


Figure A-67.—Specimen near 50% disintegration.

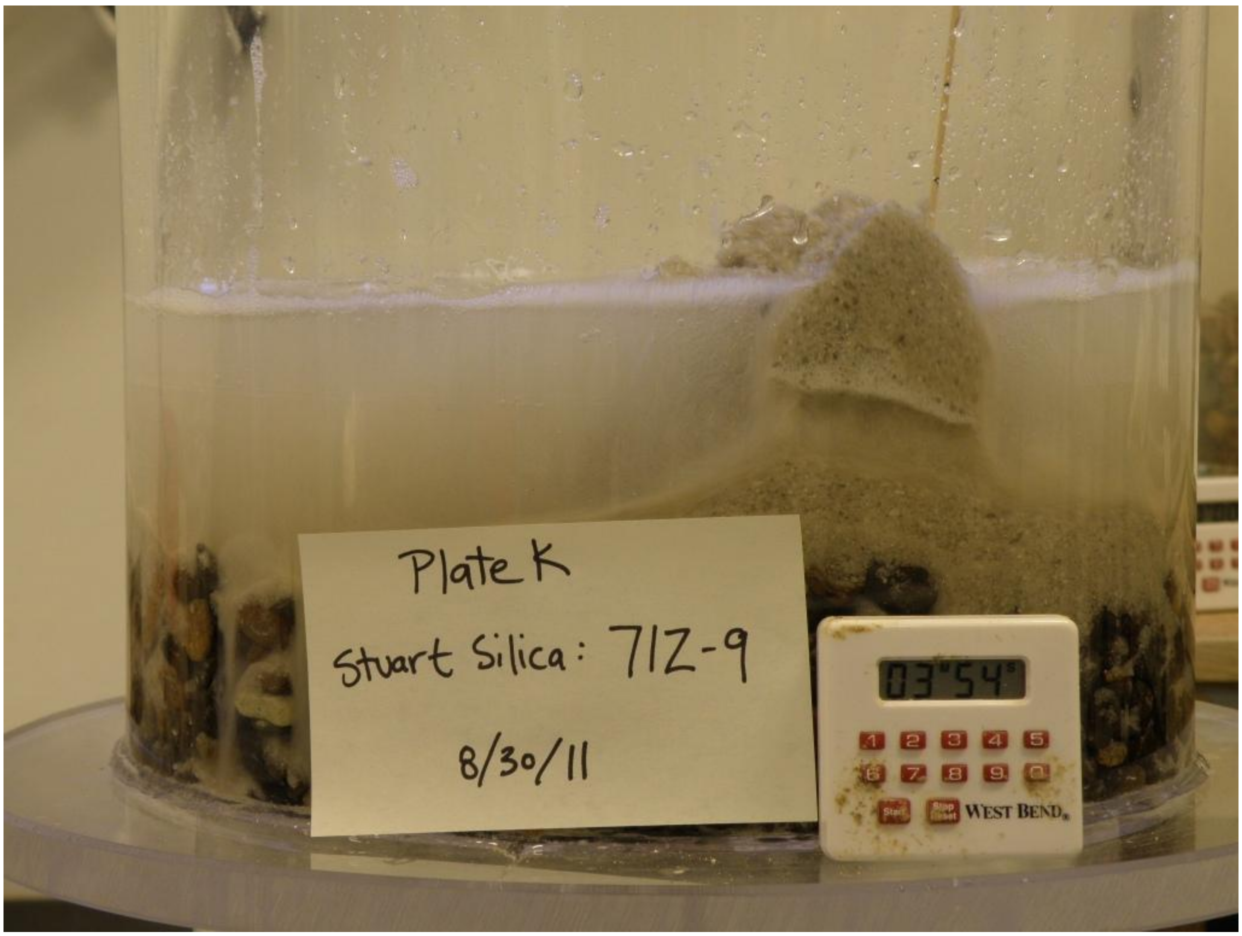


Figure A-68.—Specimen at failure.

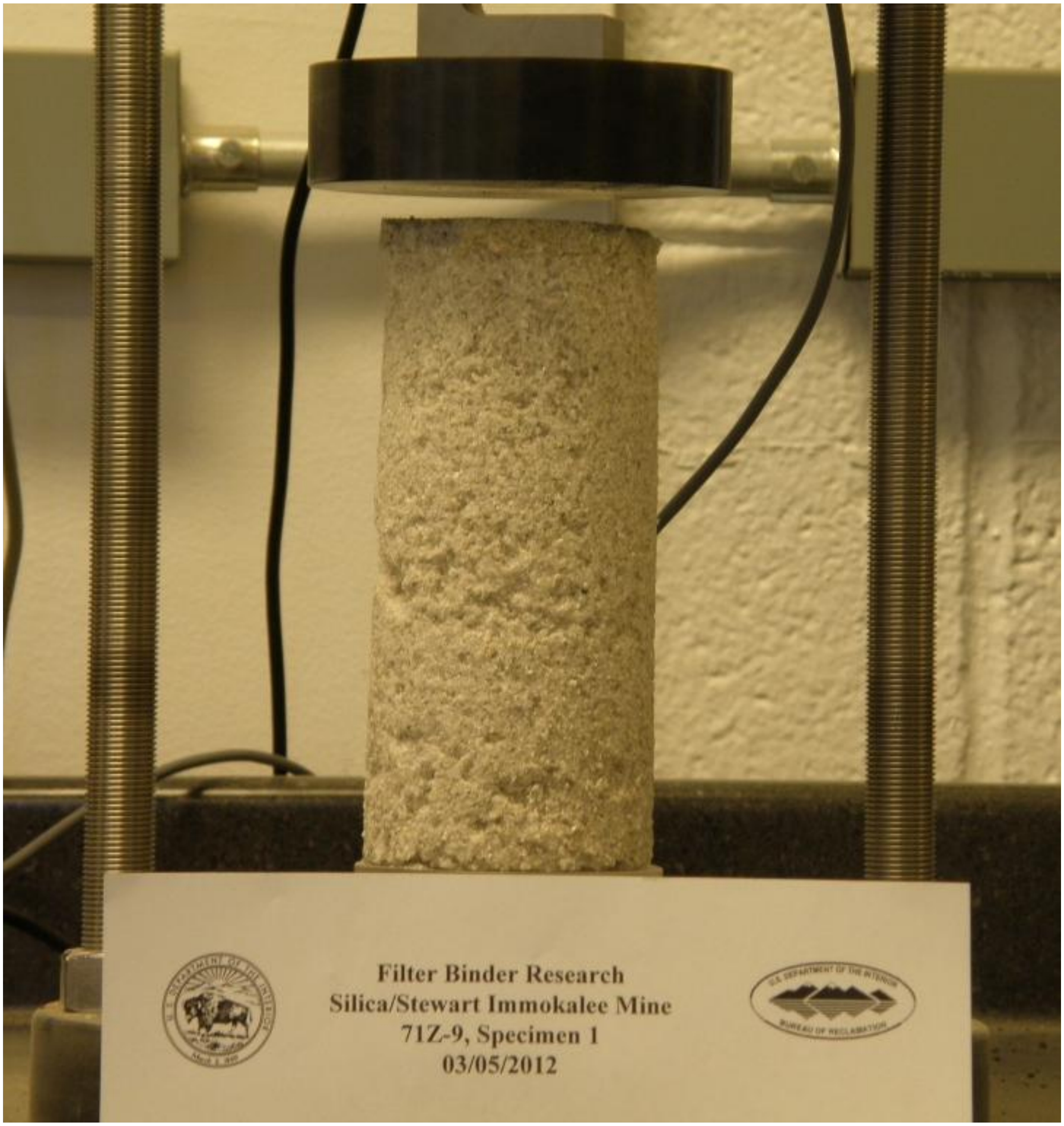


Figure A-69.—Specimen before UCS Test.

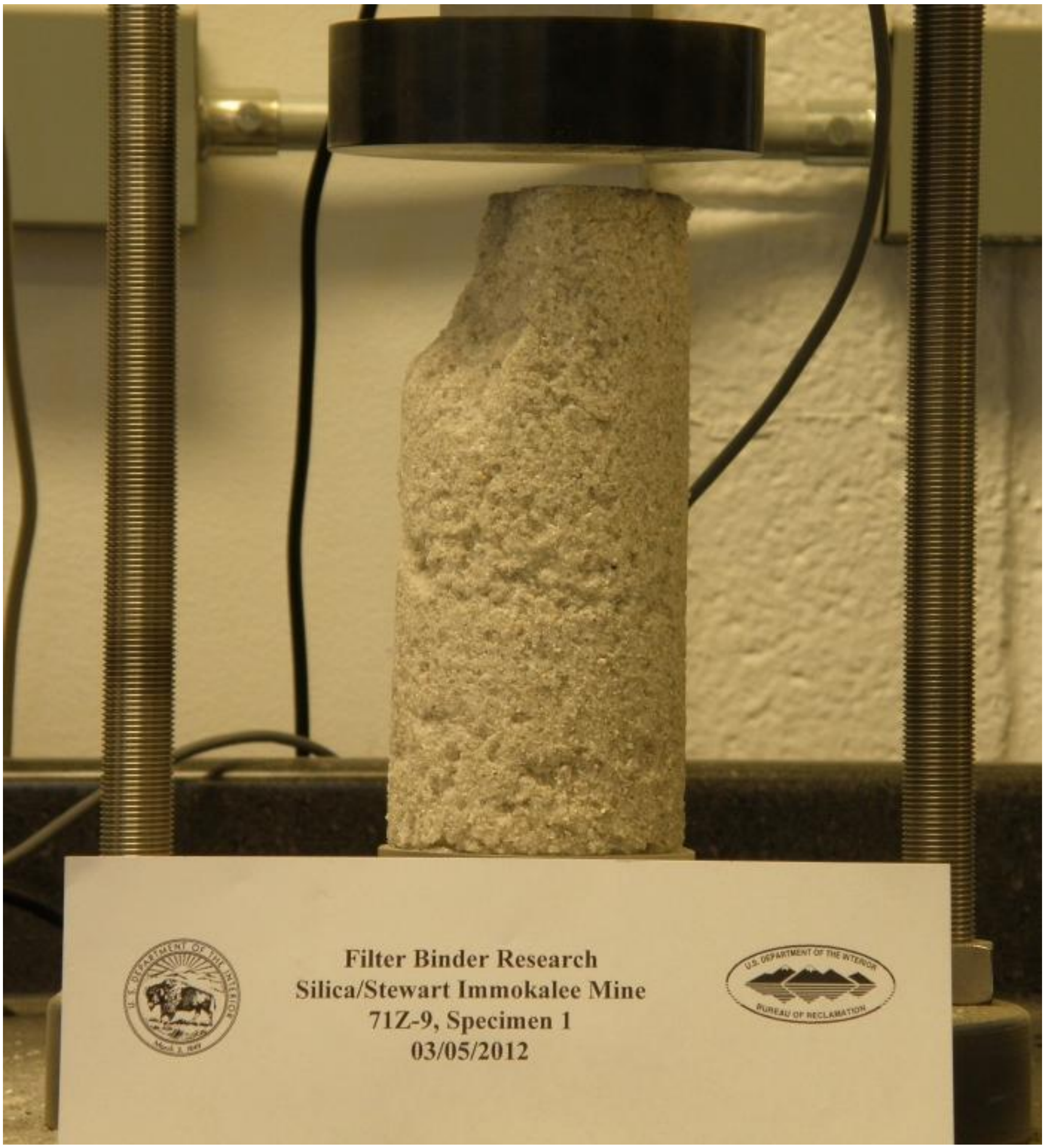


Figure A-70.—Specimen at failure.

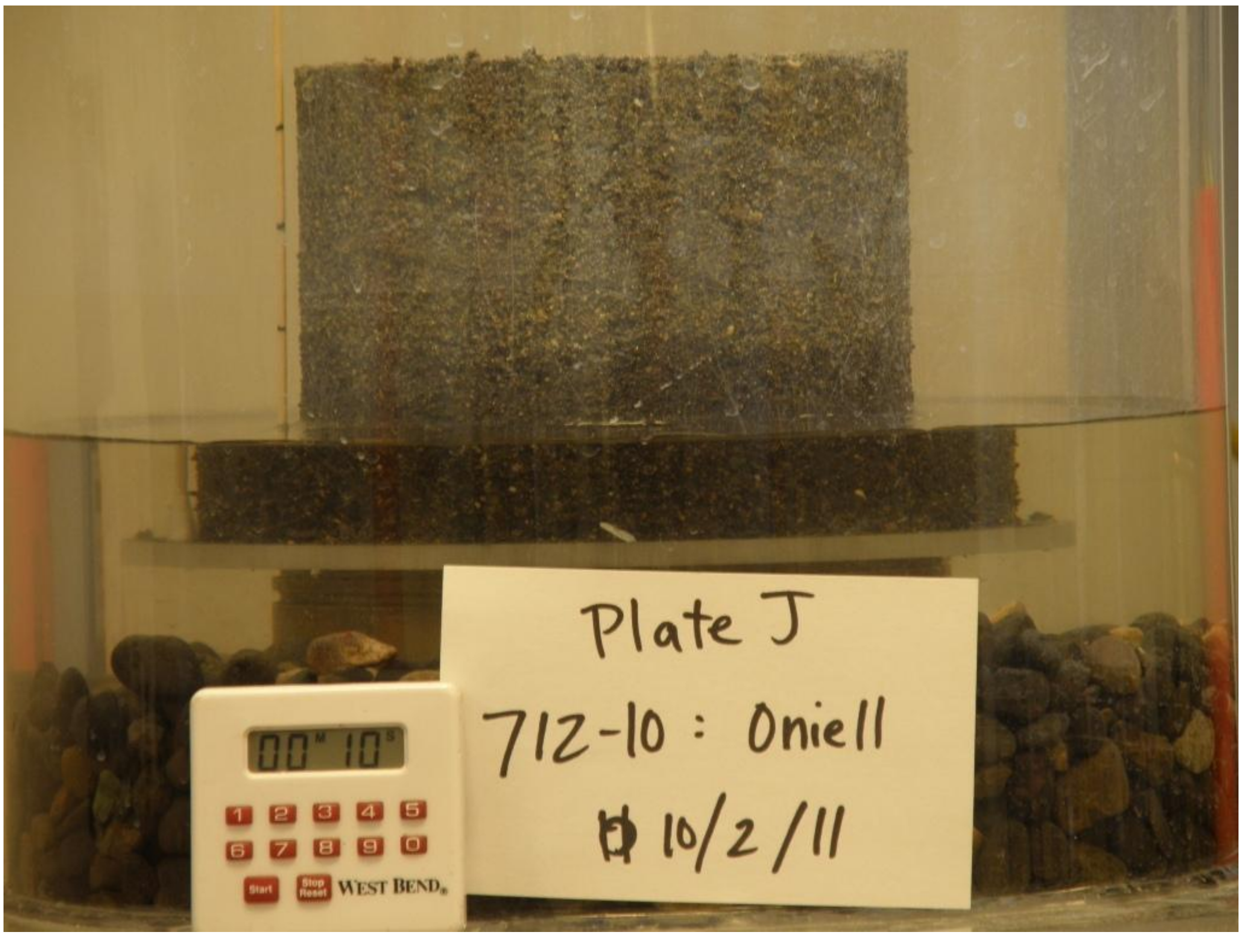


Figure A-71.—Oniell specimen at start of Sand Castle Test.

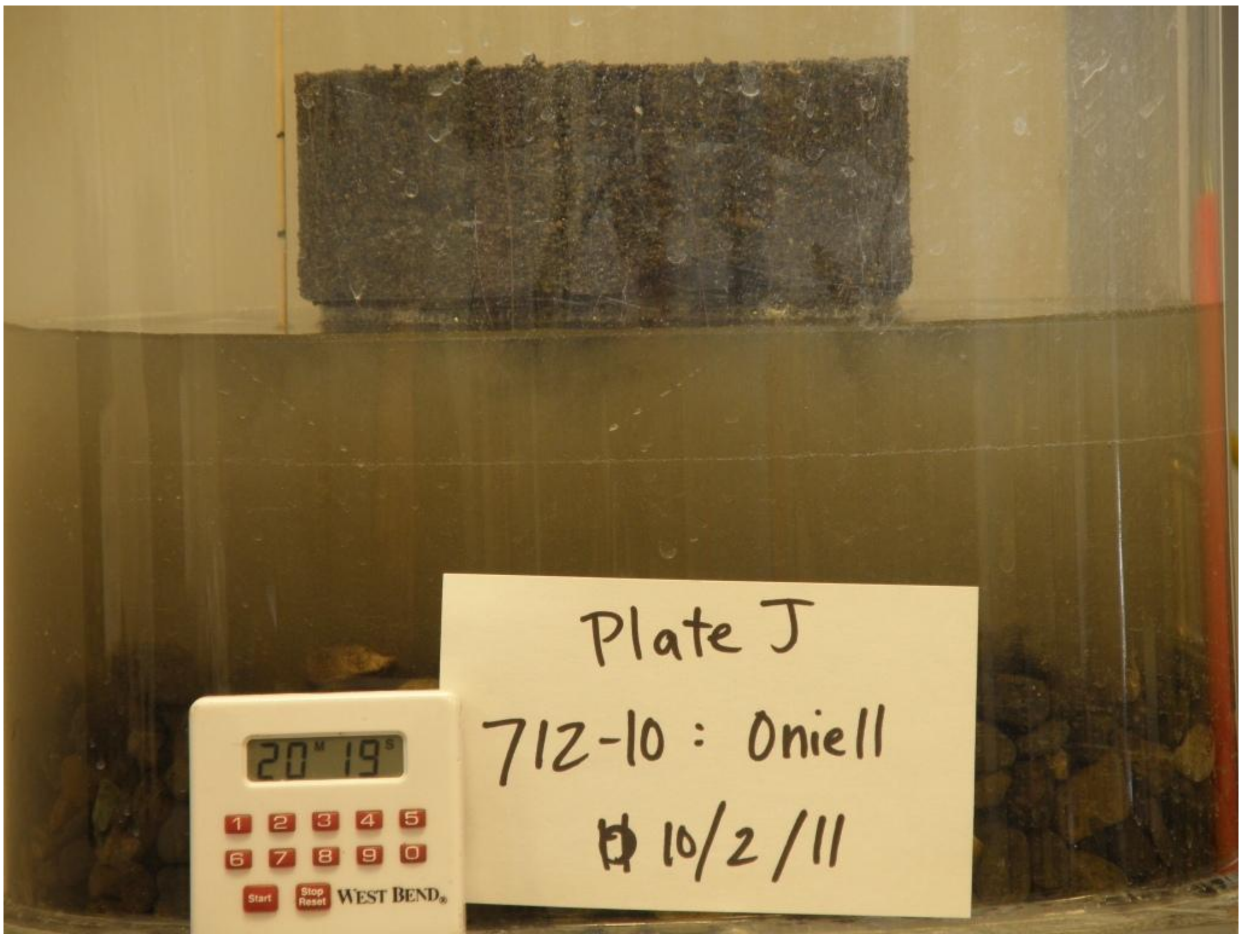


Figure A-72.—Water level increased to 2 inches.

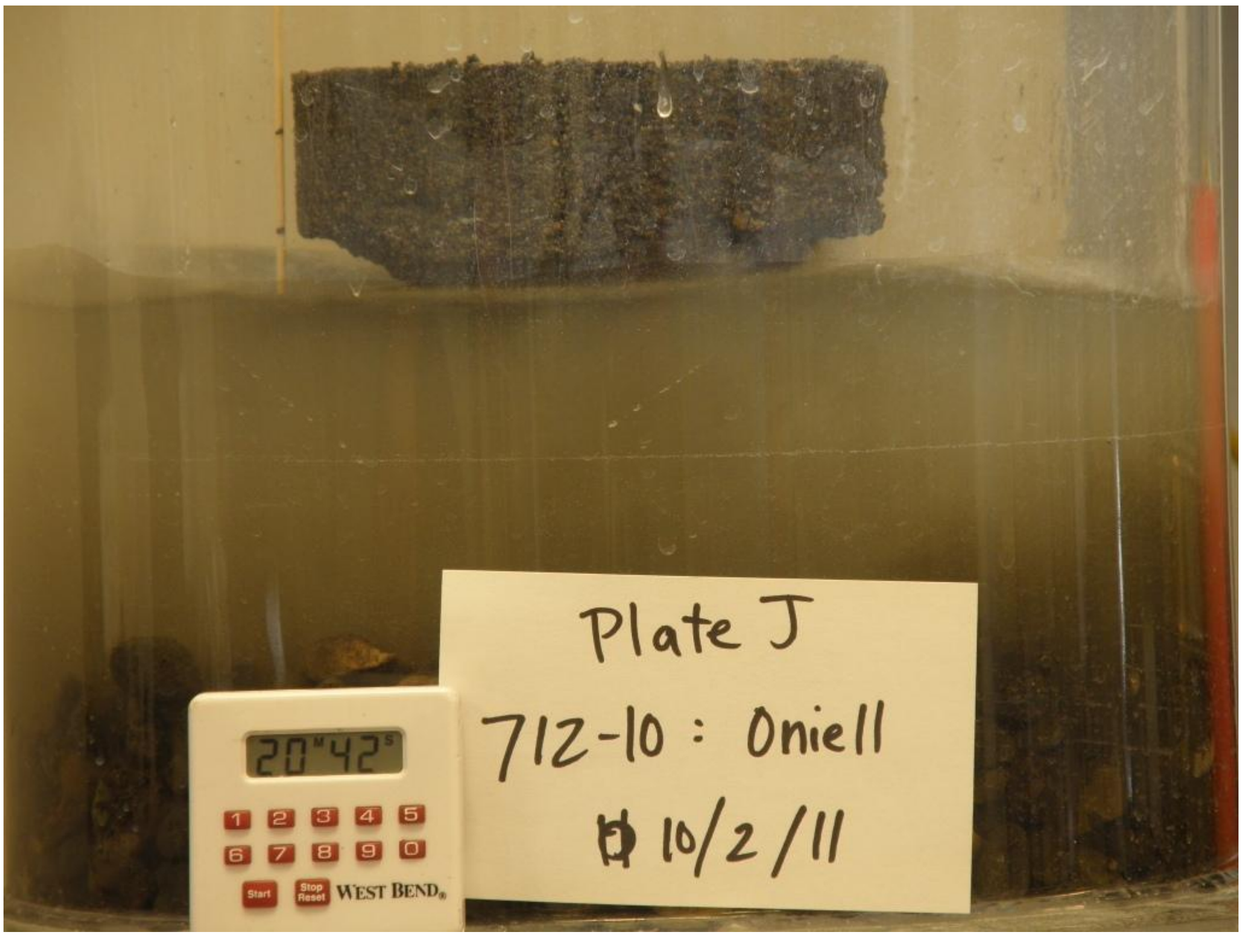


Figure A-73.—Specimen immediately before failure.

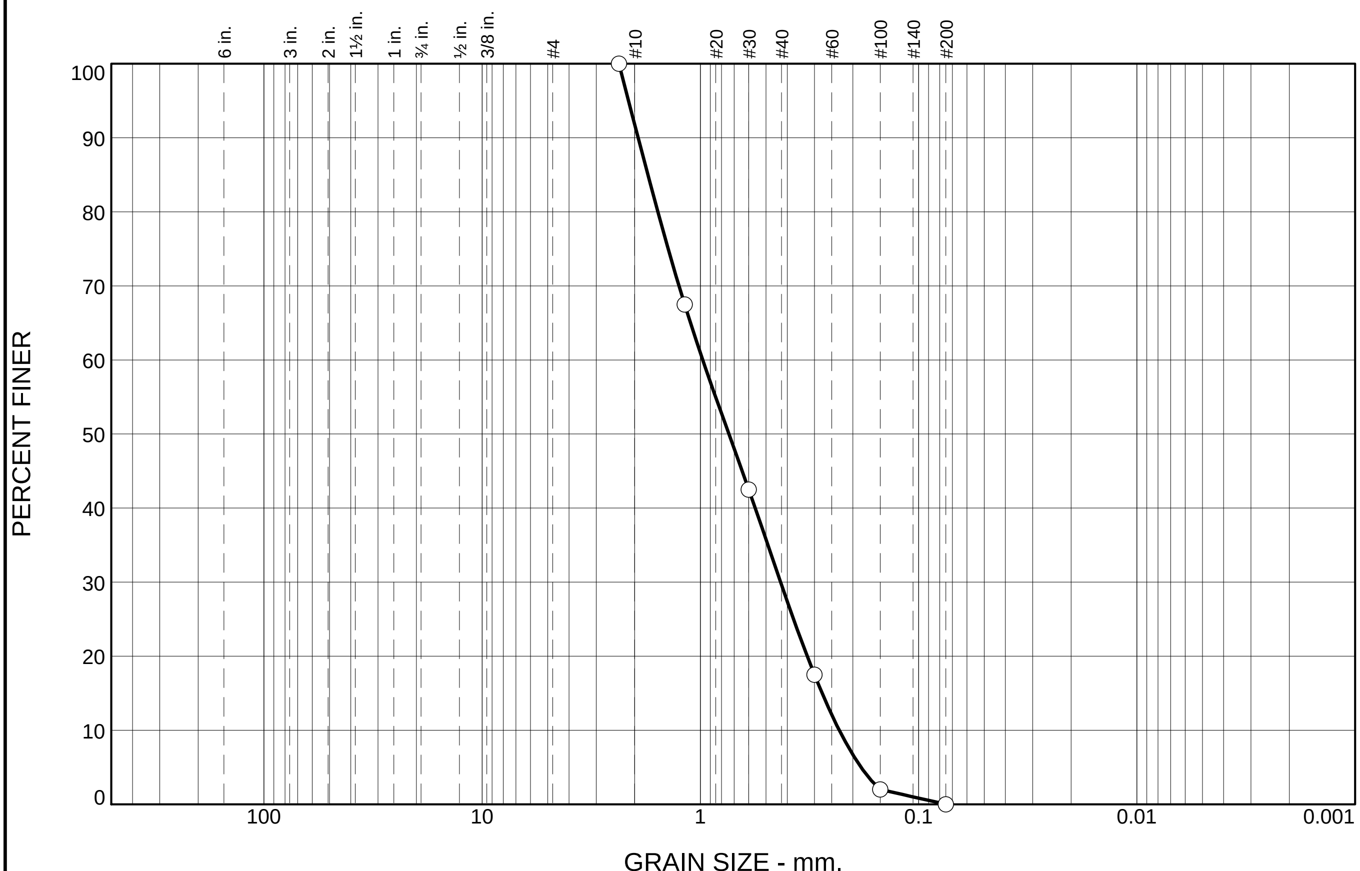
Figure A-74.—Oniell before UCS Test.

Figure A-75.—Oniell specimen at failure.

APPENDIX B

Grain Size Distribution Reports

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	8.2	62.1	29.7	0.0	0.0

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#8	100.0	80.0 - 100.0	
#16	67.5	50.0 - 85.0	
#30	42.5	25.0 - 60.0	
#50	17.5	10.0 - 30.0	
#100	2.0	2.0 - 10.0	
#200	0.0		

* ASTM C 33 - Sand

Material Description

SP - POORLY GRADED SAND

Atterberg Limits

PL= NP LL= NV PI= NP

Coefficients

D_{90}= 1.9278 D_{85}= 1.7392 D_{60}= 0.9750
D_{50}= 0.7399 D_{30}= 0.4288 D_{15}= 0.2767
D_{10}= 0.2309 C_u= 4.22 C_c= 0.82

Classification

USCS= SP AASHTO= A-1-b

Remarks

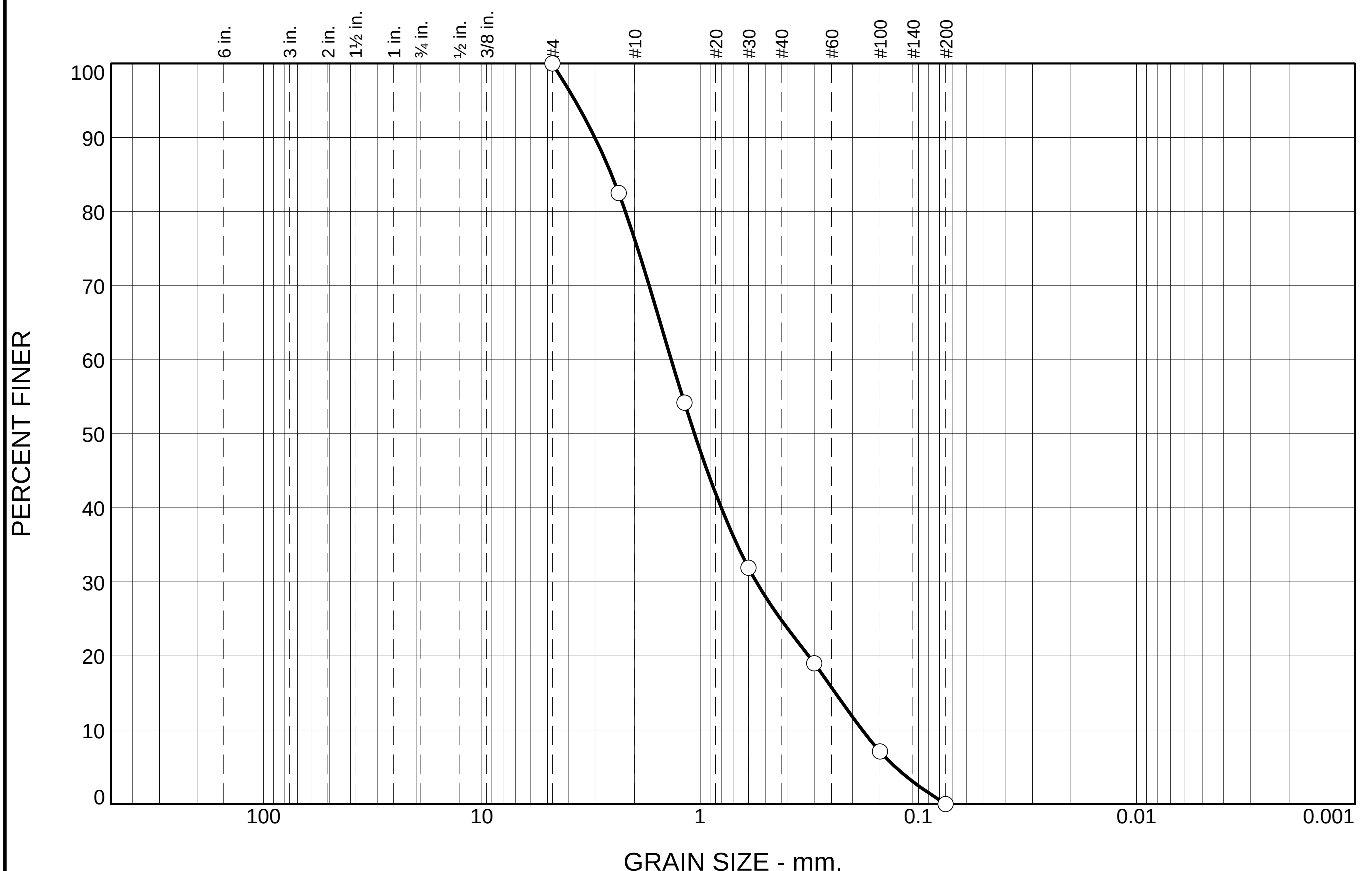
Location: Colorado Natural Silica Sand
Sample Number: 36F-1136 (2011)
Date: 7/25/2011

BUREAU OF RECLAMATION

Client: USACE-RMC & USBR-DSO
Project: Binders in Filter Material
Project No: BINDR **Figure** B-1

Tested By: B. Jackson **Checked By:** R. Rinehart

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	23.6	51.5	24.9	0.0	0.0

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0	95.0 - 100.0	
#8	82.5	80.0 - 100.0	
#16	54.2	50.0 - 85.0	
#30	31.9	25.0 - 60.0	
#50	19.0	10.0 - 30.0	
#100	7.1	2.0 - 10.0	
#200	0.0		

* ASTM C 33 - Sand

Material Description

SW - WELL GRADED SAND

Atterberg Limits

PL= NP LL= NV PI= NP

Coefficients

D_{90}= 3.0355 D_{85}= 2.5476 D_{60}= 1.3555
D_{50}= 1.0613 D_{30}= 0.5527 D_{15}= 0.2398
D_{10}= 0.1807 C_u= 7.50 C_c= 1.25

Classification

USCS= SW AASHTO= A-1-b

Remarks

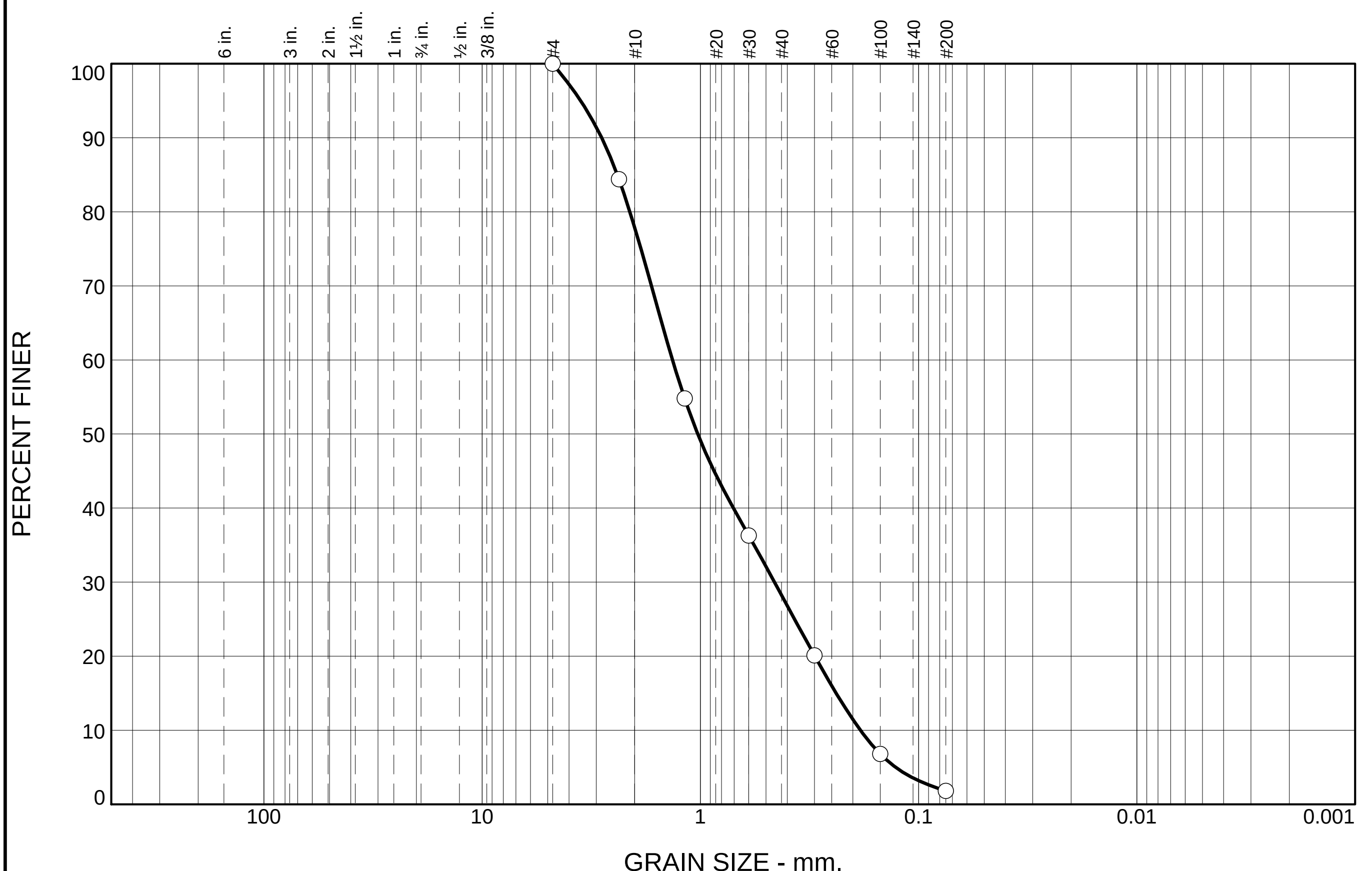
Location: Basalt Hill, Manufactured Basalt Sand, California
Sample Number: 36F-1137 (2011)
Date: 8/23/2011

BUREAU OF RECLAMATION

Client: USACE-RMC & USBR-DSO
Project: Binders in Filter Material
Project No: BINDR **Figure** B-2

Tested By: K. Ngozi-Bullock **Checked By:** R. Rinehart

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	22.1	49.6	26.5	1.8	

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0	95.0 - 100.0	
#8	84.4	80.0 - 100.0	
#16	54.8	50.0 - 85.0	
#30	36.3	25.0 - 60.0	
#50	20.1	10.0 - 30.0	
#100	6.8	2.0 - 10.0	
#200	1.8		

* ASTM C 33 - Sand

Material Description

SP - POORLY GRADED SAND

Atterberg Limits

PL= NP LL= NV PI= NP

Coefficients

D_{90}= 2.8320 D_{85}= 2.4009 D_{60}= 1.3412
D_{50}= 1.0278 D_{30}= 0.4576 D_{15}= 0.2386
D_{10}= 0.1848 C_u= 7.26 C_c= 0.85

Classification

USCS= SP AASHTO= A-1-b

Remarks

fines assumed to be nonplastic, parially manufactured (containing 20-30% crushed material)

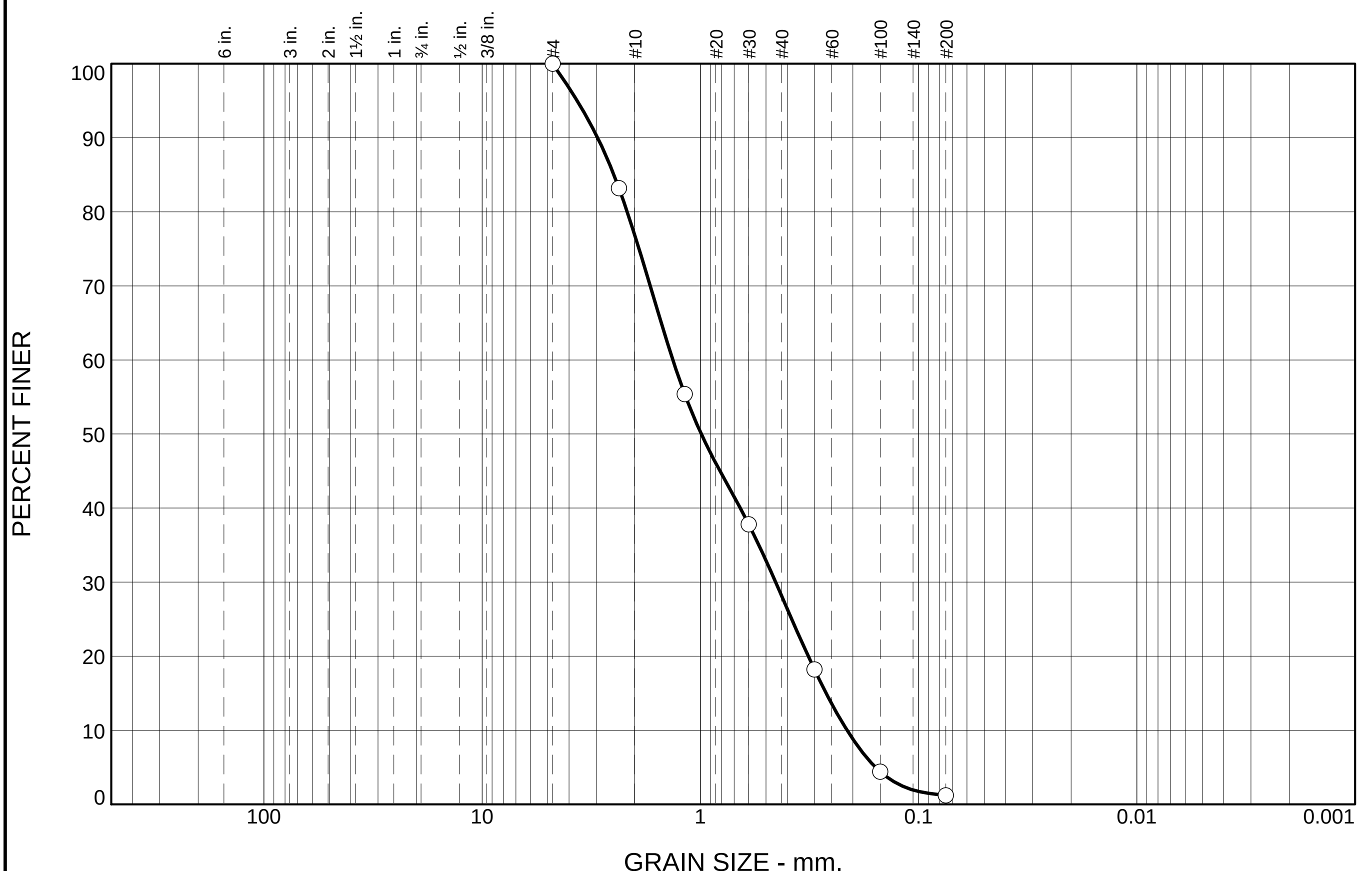
Location: Teichert Aggregate, Hope Creek Alluvium, California
Sample Number: 36F-1138 (2011)
Date: 7/22/2010

BUREAU OF RECLAMATION

Client: USACE-RMC & USBR-DSO
Project: Binders in Filter Material
Project No: BINDR **Figure** B-3

Tested By: P. Irey **Checked By:** R. Rinehart

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	23.1	48.7	27.0	1.2	

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0	95.0 - 100.0	
#8	83.2	80.0 - 100.0	
#16	55.4	50.0 - 85.0	
#30	37.8	25.0 - 60.0	
#50	18.2	10.0 - 30.0	
#100	4.4	2.0 - 10.0	
#200	1.2		

* ASTM C 33 - Sand

Material Description

SP - POORLY GRADED SAND
Concrete Sand

Atterberg Limits

PL= NP LL= NV PI= NP

Coefficients

D_{90}= 2.9562 D_{85}= 2.4896 D_{60}= 1.3359
D_{50}= 0.9901 D_{30}= 0.4521 D_{15}= 0.2652
D_{10}= 0.2127 C_u= 6.28 C_c= 0.72

Classification

USCS= SP AASHTO= A-1-b

Remarks

fines assumed to be non-plastic

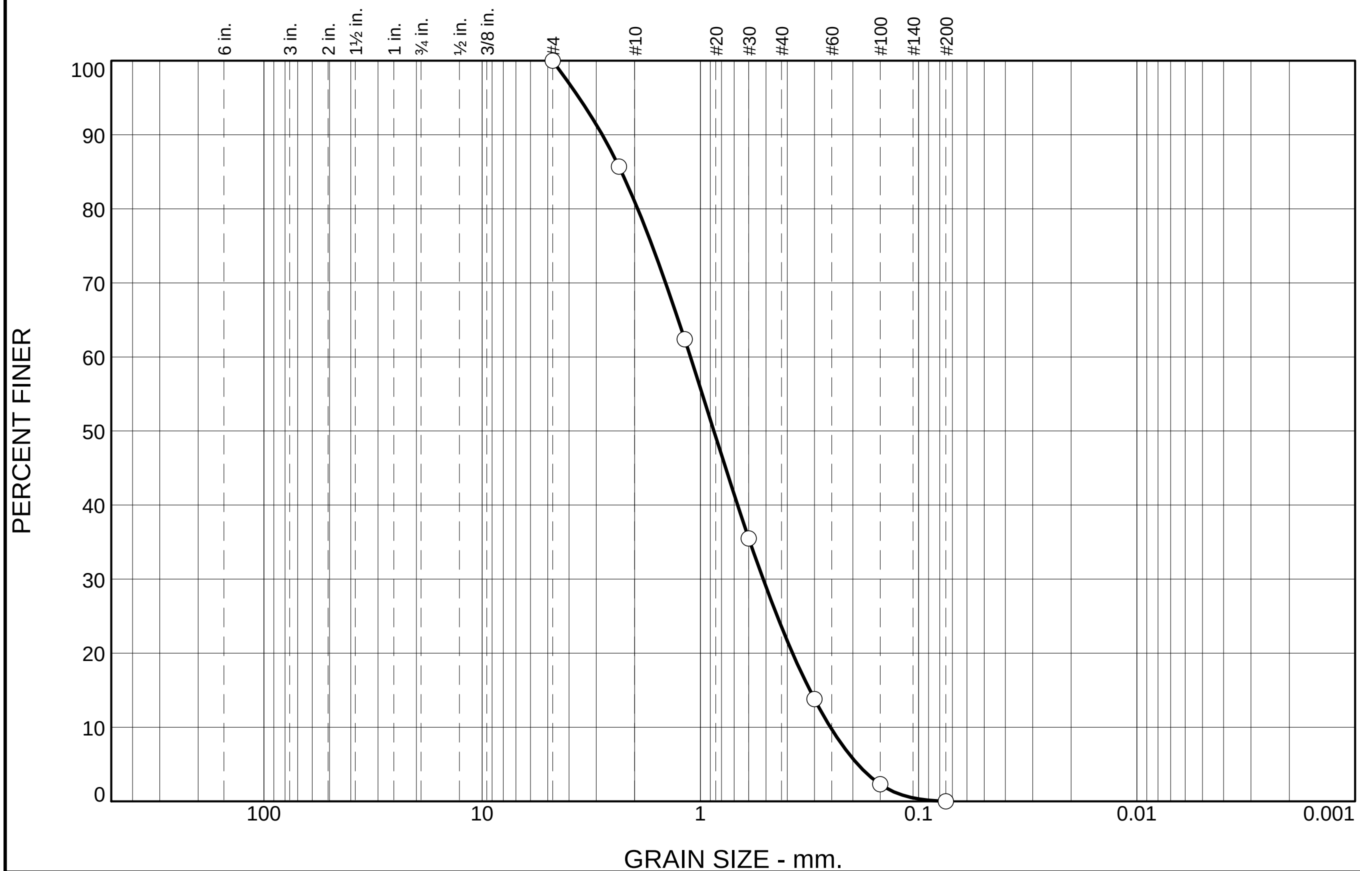
Location: Marks & Son Cemex, Orestimba Creek Alluvium, California
Sample Number: 36F-1139 (2011)
Date: 7/22/2010

BUREAU OF RECLAMATION

Client: USACE-RMC & USBR-DSO
Project: Binders in Filter Material
Project No: BINDR **Figure** B-4

Tested By: P. Irey **Checked By:** R. Rinehart

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	19.0	57.4	23.6	0.0	0.0

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0	95.0 - 100.0	
#8	85.7	80.0 - 100.0	
#16	62.4	50.0 - 85.0	
#30	35.5	25.0 - 60.0	
#50	13.8	10.0 - 30.0	
#100	2.3	2.0 - 10.0	
#200	0.0		

* ASTM C 33 - Sand

Material Description

SP - POORLY GRADED SAND

Atterberg Limits

PL= NP LL= NV PI= NP

Coefficients

D_{90}= 2.8157 D_{85}= 2.2991 D_{60}= 1.1103
D_{50}= 0.8664 D_{30}= 0.5155 D_{15}= 0.3148
D_{10}= 0.2534 C_u= 4.38 C_c= 0.94

Classification

USCS= SP AASHTO= A-1-b

Remarks

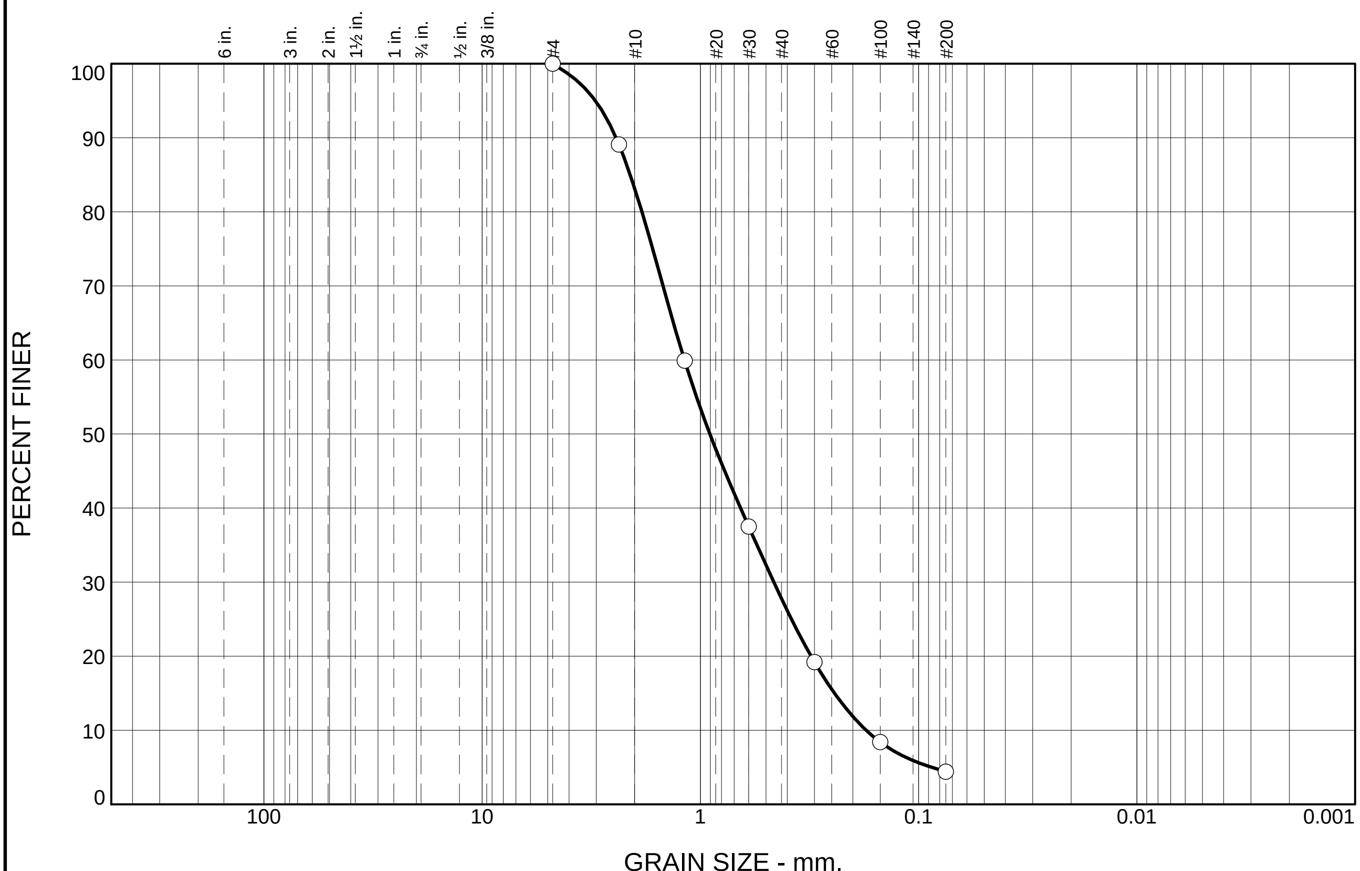
Location: Triangle Rock, Los Banos Creek Alluvium, California
Sample Number: 36F-1140 (2011)
Date: 9/15/2011

BUREAU OF RECLAMATION

Client: USACE-RMC & USBR-DSO
Project: Binders in Filter Material
Project No: BINDR **Figure** B-5

Tested By: K. Ngozi-Bullock **Checked By:** R. Rinehart

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	16.8	55.4	23.4	4.4	

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0	95.0 - 100.0	
#8	89.1	80.0 - 100.0	
#16	59.9	50.0 - 85.0	
#30	37.5	25.0 - 60.0	
#50	19.2	10.0 - 30.0	
#100	8.4	2.0 - 10.0	
#200	4.4		

* ASTM C 33 - Sand

Material Description

SW - WELL GRADED SAND

Atterberg Limits

PL= NP LL= NV PI= NP

Coefficients

D_{90}= 2.4318 D_{85}= 2.0962 D_{60}= 1.1829
D_{50}= 0.9042 D_{30}= 0.4607 D_{15}= 0.2429
D_{10}= 0.1739 C_u= 6.80 C_c= 1.03

Classification

USCS= SW AASHTO= A-1-b

Remarks

fines assumed to be non-plastic

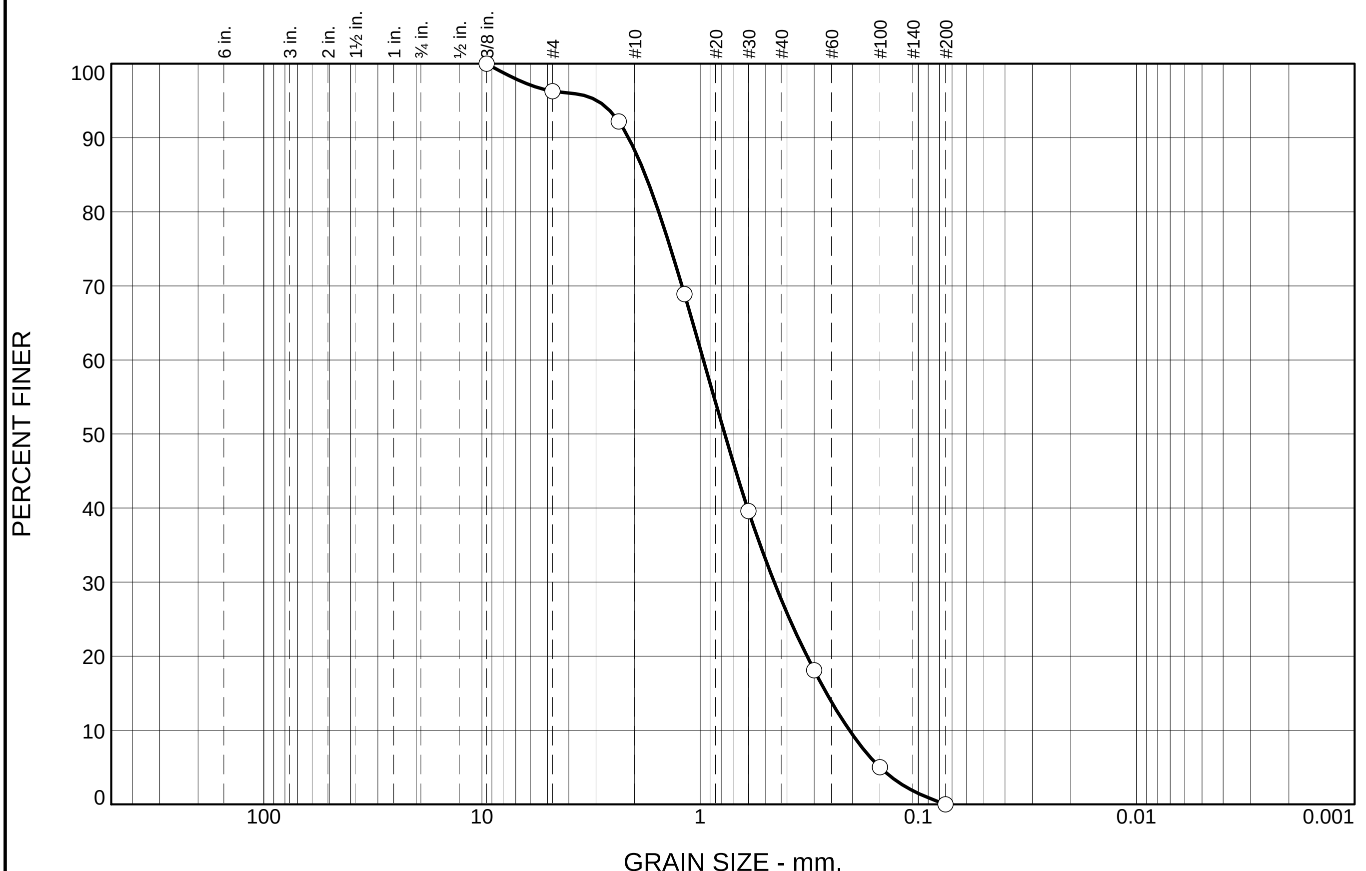
Location: Granite Rock - Manufactured Granite Sand, CA
Sample Number: 36F-1141 (2011)

Date: 7/22/2010

BUREAU OF RECLAMATION	**Client:** USACE-RMC & USBR-DSO **Project:** Binders in Filter Material **Project No:** BINDR **Figure** B-6

Tested By: P. Irey **Checked By:** R. Rinehart

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	3.7	7.9	60.7	27.7	0.0	0.0

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
.375	100.0	100.0 - 100.0	
#4	96.3	95.0 - 100.0	
#8	92.2	80.0 - 100.0	
#16	68.9	50.0 - 85.0	
#30	39.6	25.0 - 60.0	
#50	18.1	10.0 - 30.0	
#100	5.0	2.0 - 10.0	
#200	0.0		

* ASTM C 33 - Sand

Material Description

SP - POORLY GRADED SAND

Atterberg Limits

PL= NP LL= NV PI= NP

Coefficients

D_{90}= 2.1279 D_{85}= 1.7848 D_{60}= 0.9654
D_{50}= 0.7710 D_{30}= 0.4575 D_{15}= 0.2633
D_{10}= 0.2069 C_u= 4.67 C_c= 1.05

Classification

USCS= SP AASHTO= A-1-b

Remarks

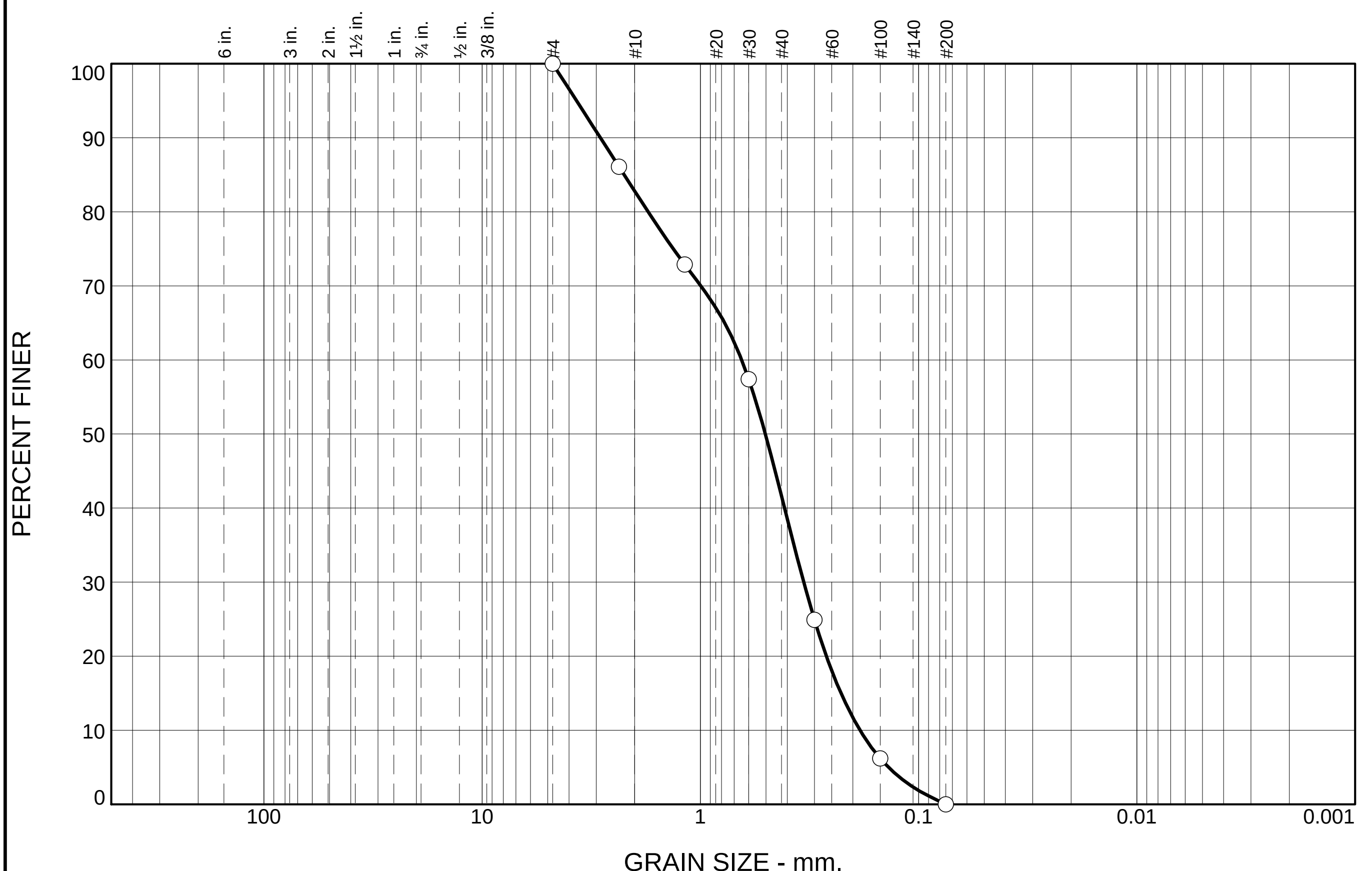
Location: Allied Recycled Concrete, Crushed Roadway Concrete, Colorado
Sample Number: 71Z-1 (2011) **Date:** 2/15/2011

BUREAU OF RECLAMATION

Client: USACE-RMC & USBR-DSO
Project: Binders in Filter Material
Project No: BINDR **Figure** B-7

Tested By: B. Jackson **Checked By:** R. Rinehart

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	17.2	41.1	41.7	0.0	0.0

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0		
#8	86.1		
#16	72.9		
#30	57.4		
#50	24.9		
#100	6.2		
#200	0.0		

* (no specification provided)

Material Description

SP - POORLY GRADED SAND

Atterberg Limits

PL= NP LL= NV PI= NP

Coefficients

D_{90}= 2.8705 D_{85}= 2.2334 D_{60}= 0.6464
D_{50}= 0.5039 D_{30}= 0.3360 D_{15}= 0.2267
D_{10}= 0.1855 C_u= 3.48 C_c= 0.94

Classification

USCS= SP AASHTO= A-1-b

Remarks

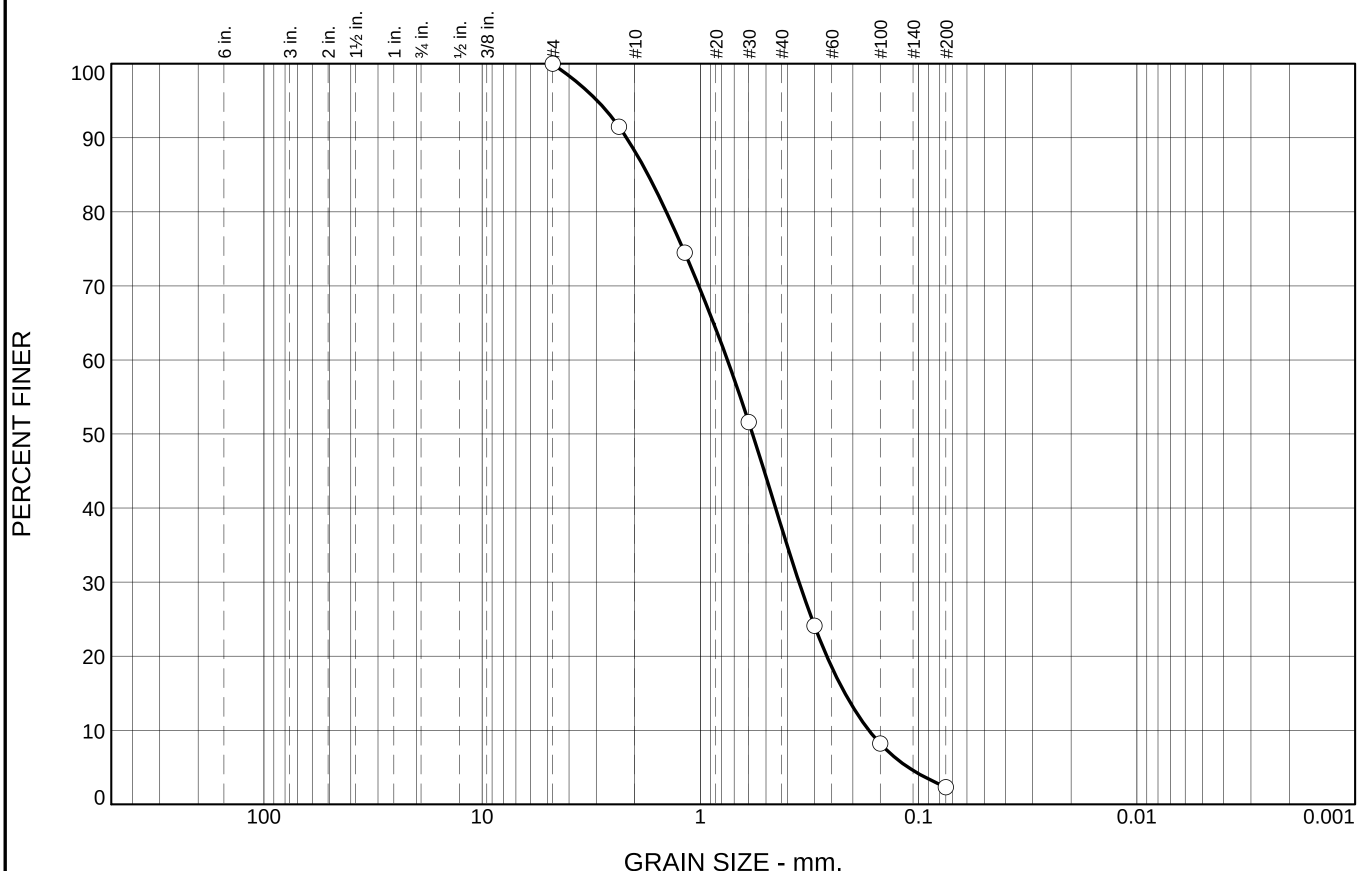
Location: Ochoco, Manufactured Sand of Alluvial Origin, Oregon
Sample Number: 71Z-2 (2011) **Date:** 8/30/2011

BUREAU OF RECLAMATION

Client: USACE-RMC & USBR-DSO
Project: Binders in Filter Material
Project No: BINDR **Figure** B-8

Tested By: K. Ngozi-Bullock **Checked By:** B. Jackson

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	11.8	50.8	35.1	2.3	

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0	95.0 - 100.0	
#8	91.5	80.0 - 100.0	
#16	74.5	50.0 - 85.0	
#30	51.6	25.0 - 60.0	
#50	24.1	10.0 - 30.0	
#100	8.2	2.0 - 10.0	
#200	2.3		

* ASTM C 33 - Sand

Material Description

SP - POORLY GRADED SAND

Atterberg Limits

PL= NP LL= NV PI= NP

Coefficients

D_{90}= 2.1787 D_{85}= 1.7369 D_{60}= 0.7518
D_{50}= 0.5763 D_{30}= 0.3530 D_{15}= 0.2176
D_{10}= 0.1690 C_u= 4.45 C_c= 0.98

Classification

USCS= SP AASHTO= A-1-b

Remarks

fines assumed to be nonplastic

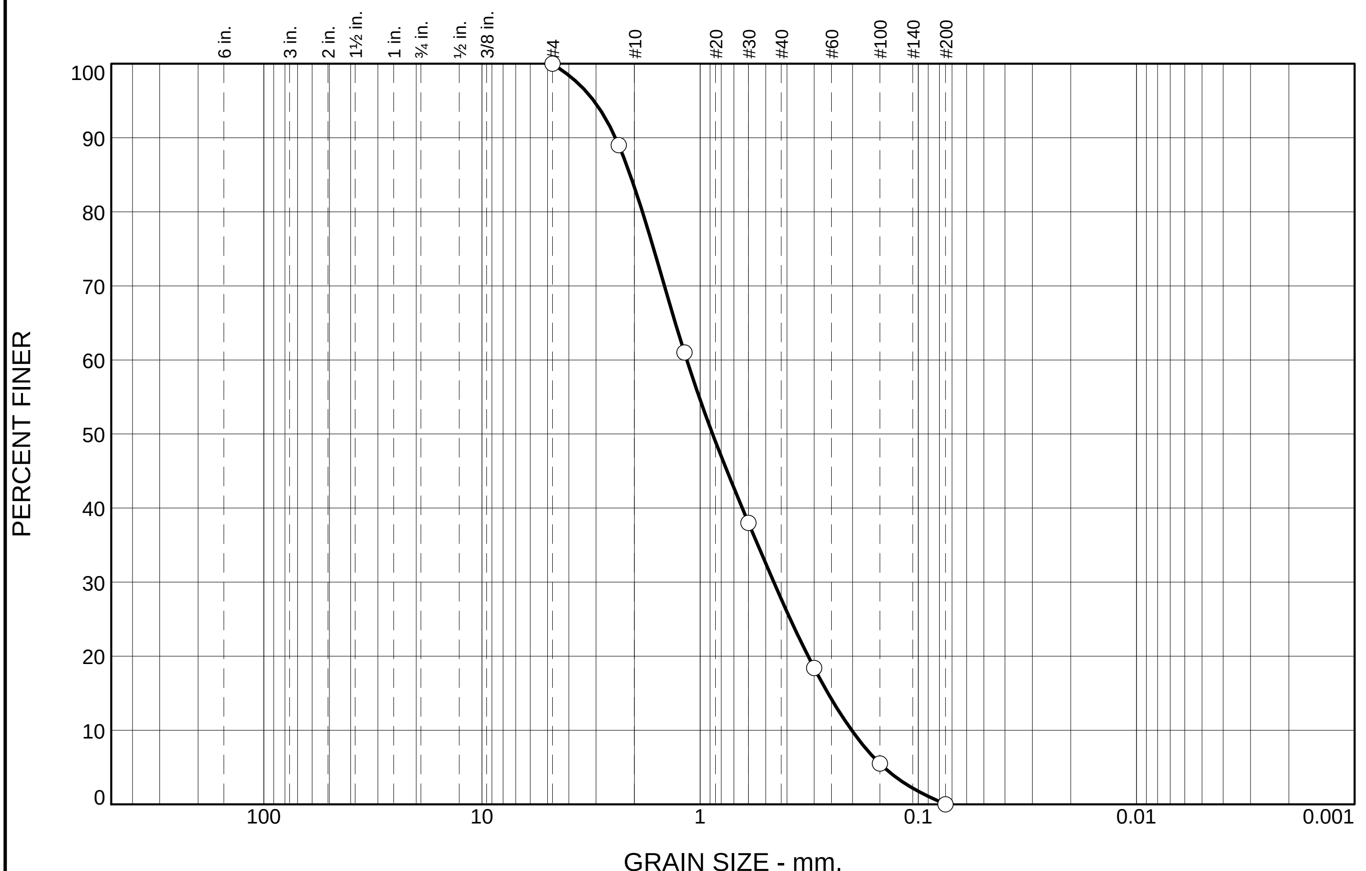
Location: Redi-Mix/Lone Pine, Crooked River Alluvium, Central Oregon
Sample Number: 71Z-3 (2011)
Date: 6/11/2010

BUREAU OF RECLAMATION

Client: USACE-RMC & USBR-DSO
Project: Binders in Filter Material
Project No: BINDR **Figure** B-9

Tested By: R. Rinehart **Checked By:** J. Fahy

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	16.7	55.6	27.7	0.0	0.0

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0	95.0 - 100.0	
#8	89.0	80.0 - 100.0	
#16	61.0	50.0 - 85.0	
#30	38.0	25.0 - 60.0	
#50	18.4	10.0 - 30.0	
#100	5.5	2.0 - 10.0	
#200	0.0		

* ASTM C 33 - Sand

Material Description

SP - POORLY GRADED SAND

Atterberg Limits

PL= NP LL= NV PI= NP

Coefficients

D_{90}= 2.4435 D_{85}= 2.0916 D_{60}= 1.1511
D_{50}= 0.8764 D_{30}= 0.4595 D_{15}= 0.2593
D_{10}= 0.2019 C_u= 5.70 C_c= 0.91

Classification

USCS= SP AASHTO= A-1-b

Remarks

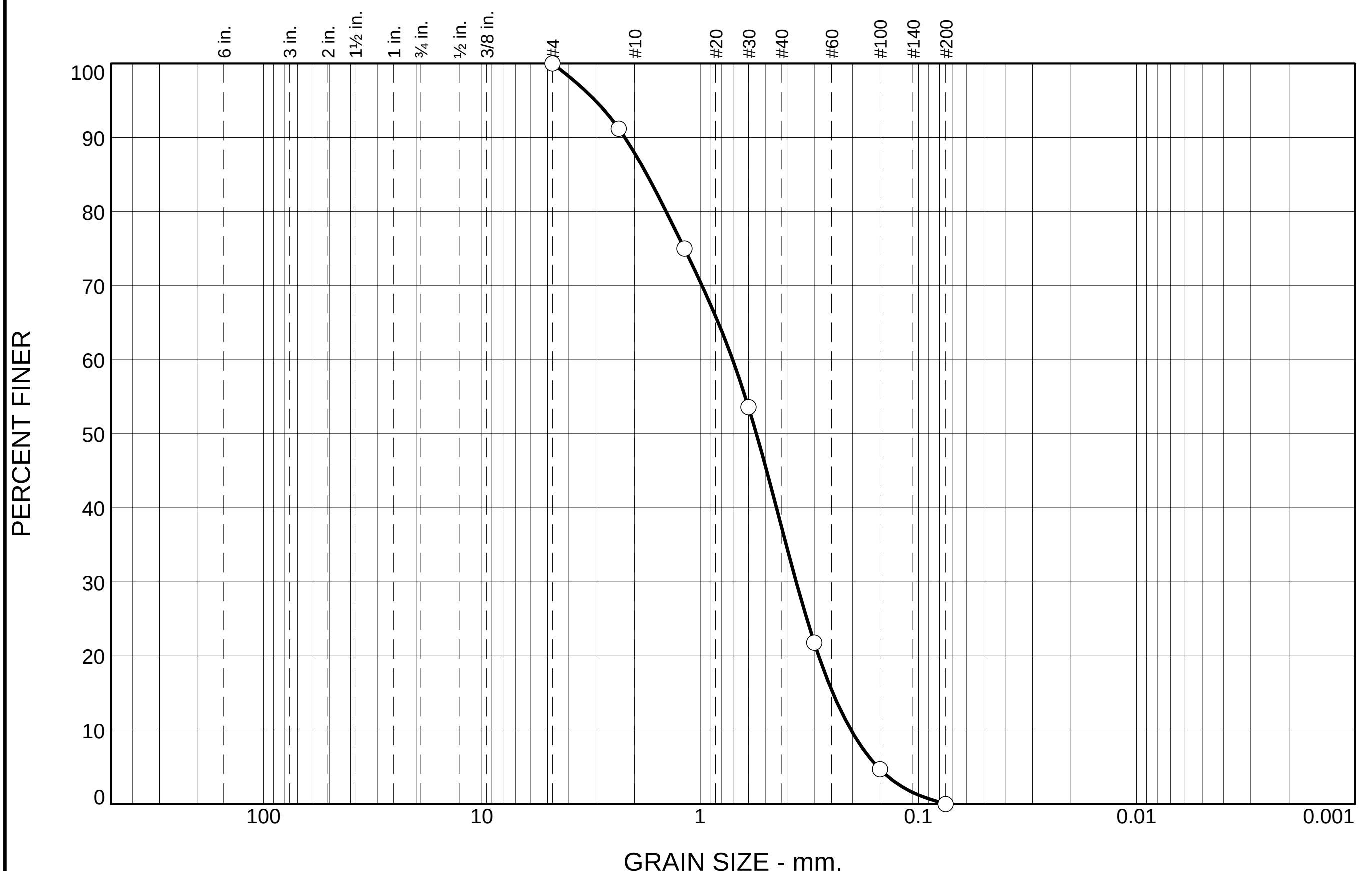
Location: Shevlin, Deschutes River Alluvium, Oregon
Sample Number: 71Z-4 (2011)
Date: 7/25/2011

BUREAU OF RECLAMATION

Client: USACE-RMC & USBR-DSO
Project: Binders in Filter Material
Project No: BINDR **Figure** B-10

Tested By: B. Jackson **Checked By:** R. Rinehart

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	12.1	50.3	37.6	0.0	0.0

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0	95.0 - 100.0	
#8	91.2	80.0 - 100.0	
#16	75.0	50.0 - 85.0	
#30	53.6	25.0 - 60.0	
#50	21.8	10.0 - 30.0	
#100	4.7	2.0 - 10.0	
#200	0.0		

* ASTM C 33 - Sand

Material Description

SP - POORLY GRADED SAND

Atterberg Limits

PL= NP LL= NV PI= NP

Coefficients

D_{90}= 2.2127 D_{85}= 1.7530 D_{60}= 0.7092
D_{50}= 0.5521 D_{30}= 0.3626 D_{15}= 0.2464
D_{10}= 0.2036 C_u= 3.48 C_c= 0.91

Classification

USCS= SP AASHTO= A-1-b

Remarks

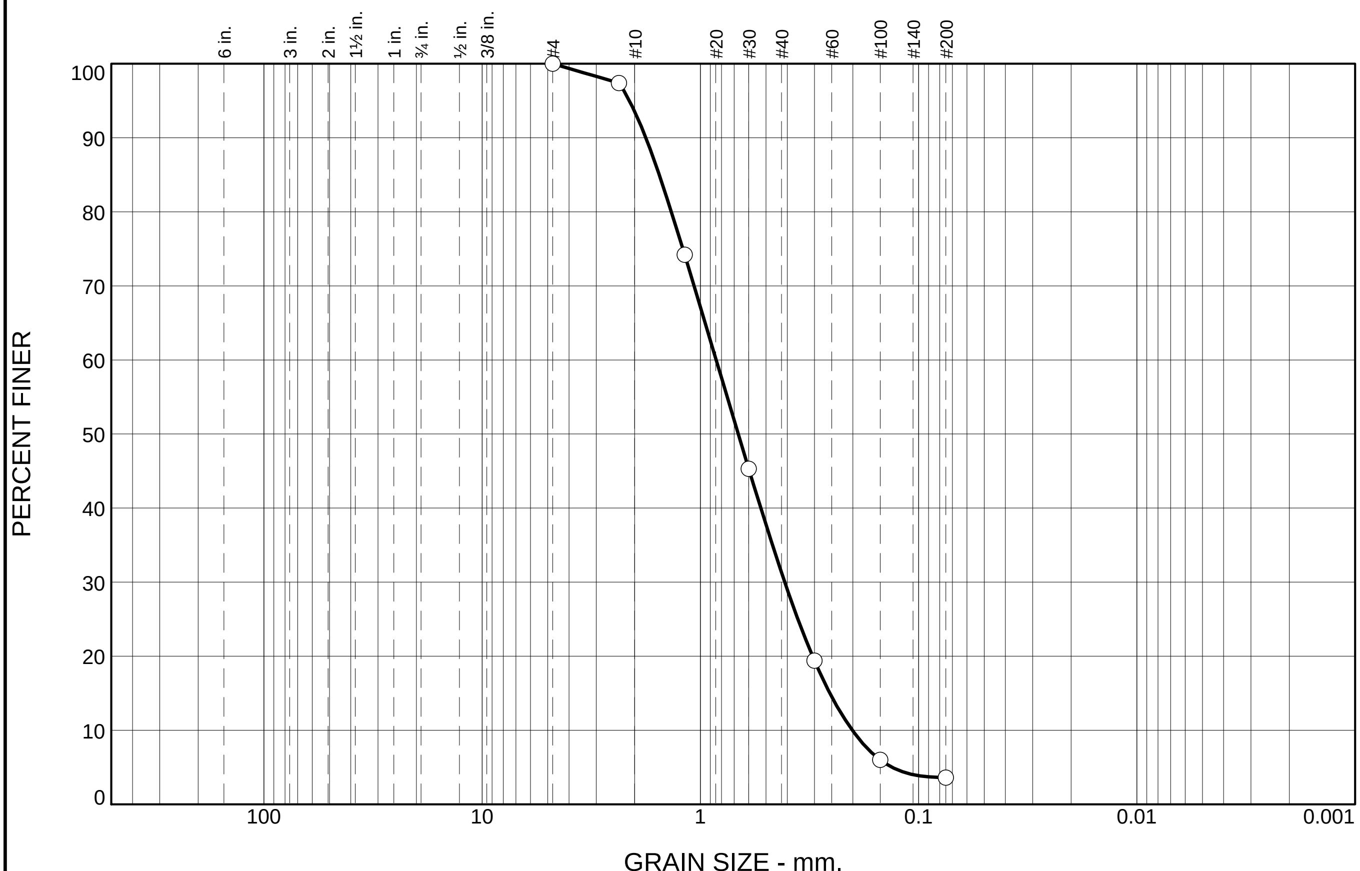
Location: Grizzly Rock Products, Crooked River Alluvium (Upper Terrace), Oregon
Sample Number: 71Z-5 (2011) **Date:** 7/25/11

BUREAU OF RECLAMATION

Client: USACE-RMC & USBR-DSO
Project: Binders in Filter Material
Project No: BINDR **Figure** B-11

Tested By: B. Jackson **Checked By:** R. Rinehart

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	6.4	62.3	27.7	3.6	

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0	95.0 - 100.0	
#8	97.4	80.0 - 100.0	
#16	74.2	50.0 - 85.0	
#30	45.3	25.0 - 60.0	
#50	19.4	10.0 - 30.0	
#100	6.0	2.0 - 10.0	
#200	3.6		

* ASTM C 33 - Sand

Material Description

SP - POORLY GRADED SAND

Atterberg Limits

PL= NP LL= NV PI= NP

Coefficients

D_{90}= 1.7776 D_{85}= 1.5428 D_{60}= 0.8461
D_{50}= 0.6703 D_{30}= 0.4104 D_{15}= 0.2550
D_{10}= 0.2013 C_u= 4.20 C_c= 0.99

Classification

USCS= SP AASHTO= A-1-b

Remarks

fines assumed to be non-plastic

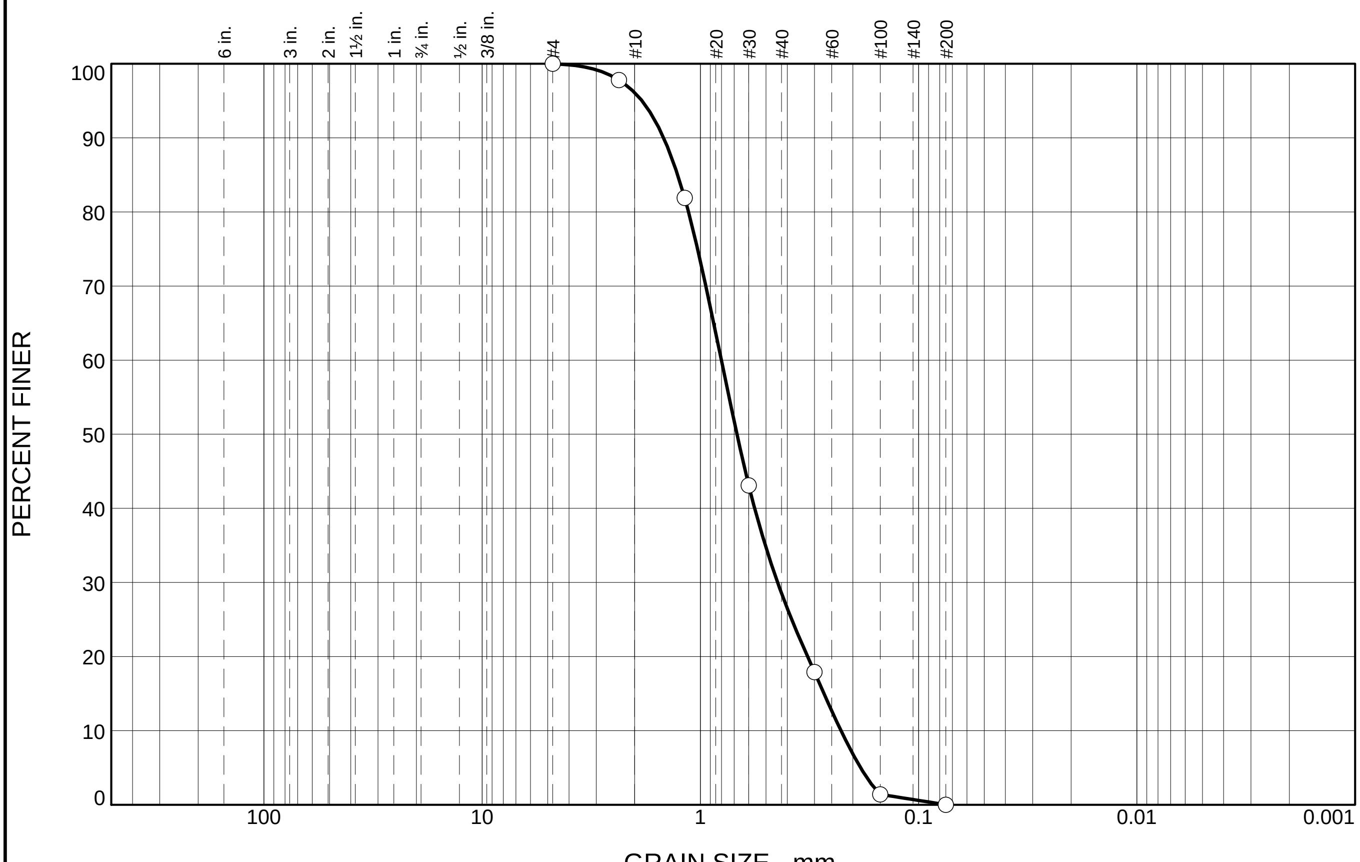
Location: Rock Products, Prinevelle Sand & Gravel, Crooked River Alluvim, Oregon
Sample Number: 71Z-6 (2011)
Date: 6/11/2010

BUREAU OF RECLAMATION

Client: USACE-RMC & USBR-DSO
Project: Binders in Filter Material
Project No: BINDR **Figure** B-12

Tested By: R. Rinehart **Checked By:** J. Fahy

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	3.9	67.5	28.6	0.0	0.0

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0	95.0 - 100.0	
#8	97.8	80.0 - 100.0	
#16	81.9	50.0 - 85.0	
#30	43.1	25.0 - 60.0	
#50	17.9	10.0 - 30.0	
#100	1.4	2.0 - 10.0	X
#200	0.0		

* ASTM C 33 - Sand

Material Description

SP - POORLY GRADED SAND

Atterberg Limits

PL= NP LL= NV PI= NP

Coefficients

D_{90}= 1.4723 D_{85}= 1.2696 D_{60}= 0.8011
D_{50}= 0.6795 D_{30}= 0.4426 D_{15}= 0.2713
D_{10}= 0.2267 C_u= 3.53 C_c= 1.08

Classification

USCS= SP AASHTO= A-1-b

Remarks

Location: Natural Cemex Silica, Florida
Sample Number: 71Z-7 (2011)

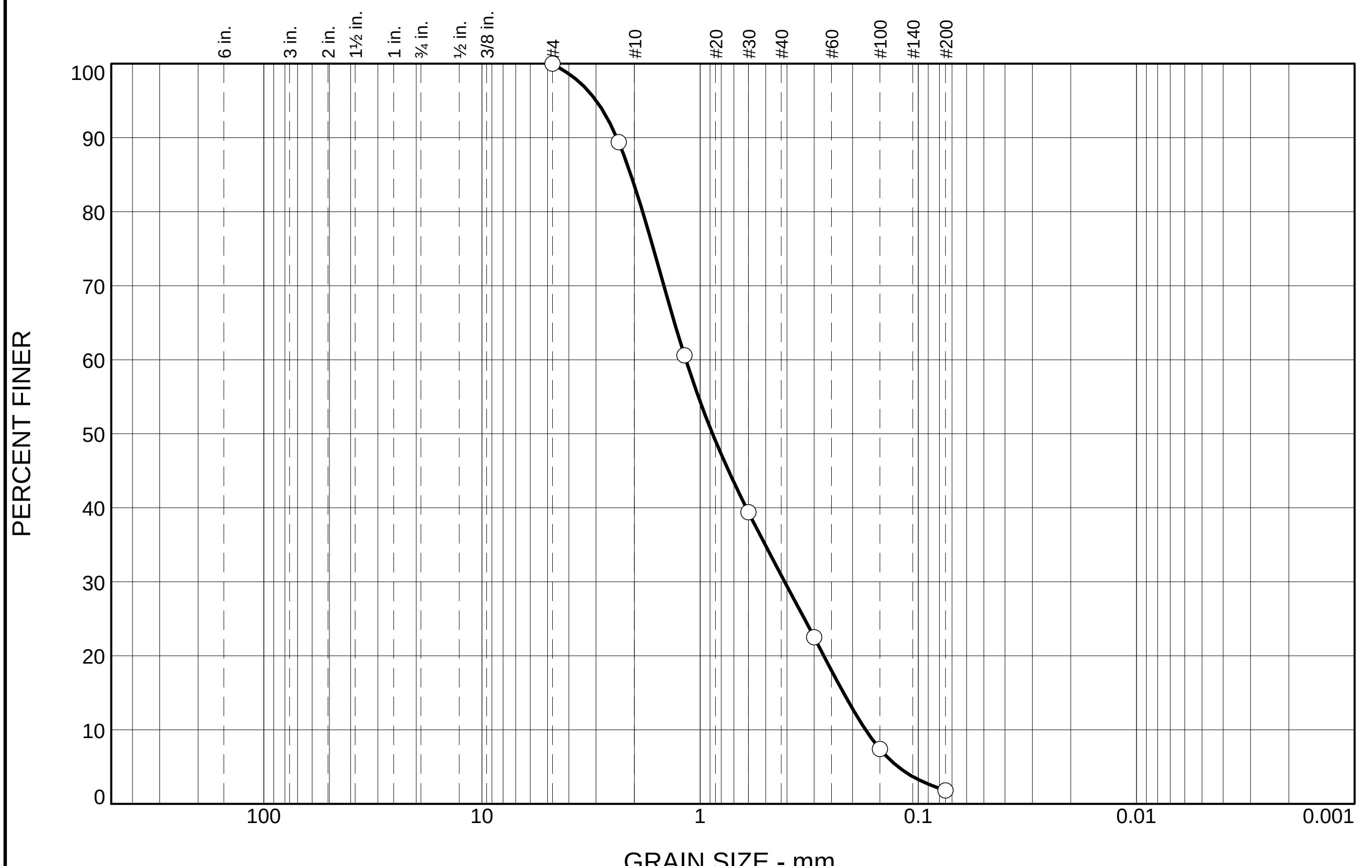
Date: 8/22/11

BUREAU OF RECLAMATION

Client: USACE-RMC & USBR-DSO
Project: Binders in Filter Material
Project No: BINDR **Figure** B-13

Tested By: K. Ngozi-Bullock **Checked By:** B. Jackson

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	16.5	52.6	29.1	1.8	

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0	95.0 - 100.0	
#8	89.4	80.0 - 100.0	
#16	60.6	50.0 - 85.0	
#30	39.4	25.0 - 60.0	
#50	22.5	10.0 - 30.0	
#100	7.4	2.0 - 10.0	
#200	1.8		

* ASTM C 33 - Sand

Material Description

SP - POORLY GRADED SAND

Atterberg Limits

PL= NP LL= NV PI= NP

Coefficients

D_{90}= 2.4078 D_{85}= 2.0767 D_{60}= 1.1626
D_{50}= 0.8766 D_{30}= 0.4095 D_{15}= 0.2202
D_{10}= 0.1744 C_u= 6.67 C_c= 0.83

Classification

USCS= SP AASHTO= A-1-b

Remarks

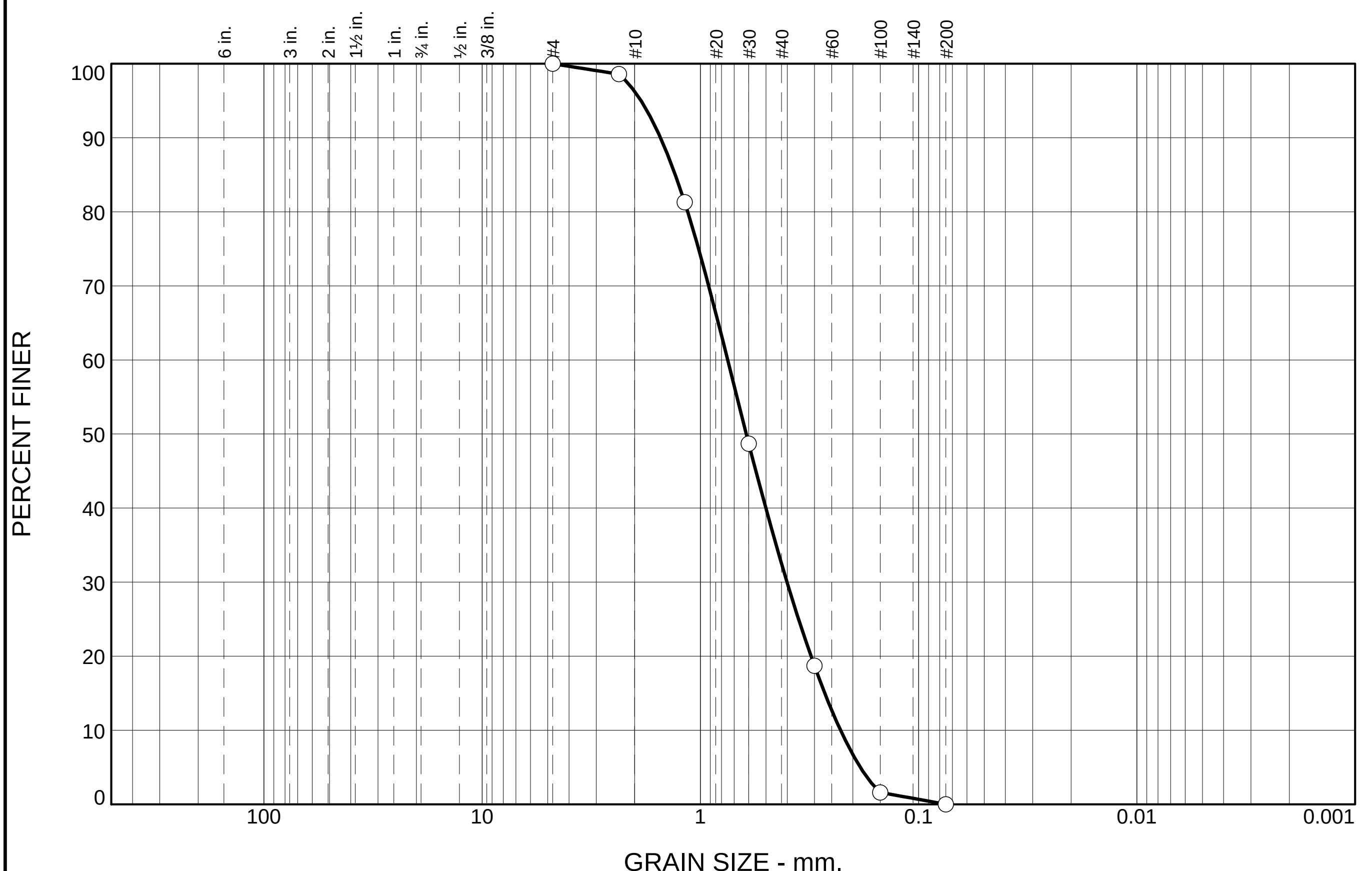
Location: Manufactured Cemex Limestone Sand, Florida
Sample Number: 71Z-8 (2011) **Date:** 7/25/2011

BUREAU OF RECLAMATION

Client: USACE-RMC & USBR-DSO
Project: Binders in Filter Material
Project No: BINDR **Figure** B-14

Tested By: B. Jackson **Checked By:** R. Rinehart

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	3.7	63.8	32.5	0.0	0.0

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0	95.0 - 100.0	
#8	98.6	80.0 - 100.0	
#16	81.3	50.0 - 85.0	
#30	48.7	25.0 - 60.0	
#50	18.7	10.0 - 30.0	
#100	1.6	2.0 - 10.0	X
#200	0.0		

* ASTM C 33 - Sand

Material Description

SP - POORLY GRADED SAND

Atterberg Limits

PL= NP LL= NV PI= NP

Coefficients

D_{90}= 1.5224 D_{85}= 1.3021 D_{60}= 0.7495
D_{50}= 0.6158 D_{30}= 0.4007 D_{15}= 0.2691
D_{10}= 0.2279 C_u= 3.29 C_c= 0.94

Classification

USCS= SP AASHTO= A-1-b

Remarks

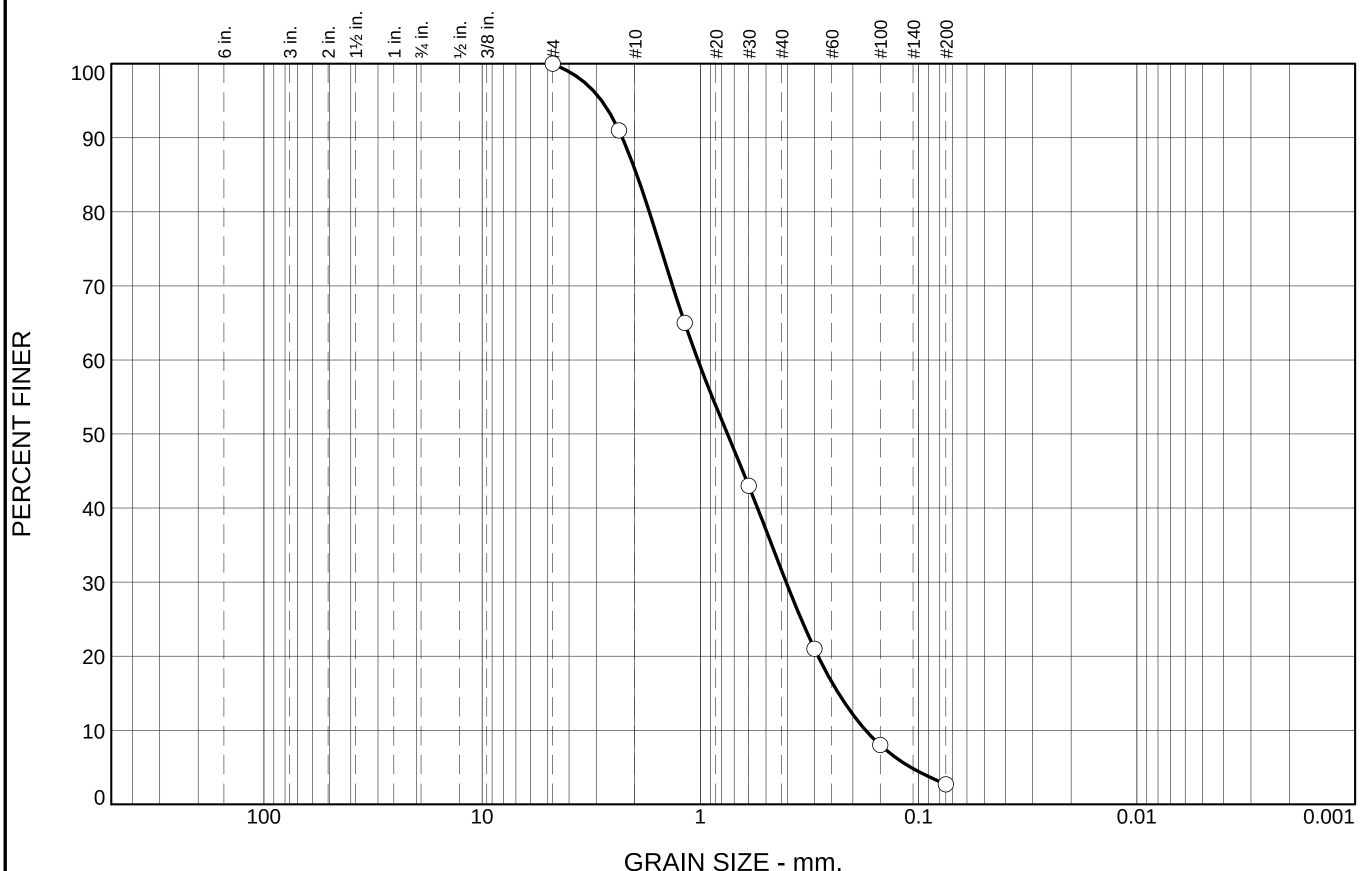
Location: Stewart Silica, Florida
Sample Number: 71Z-9 (2011)
Date: 8/15/2011

BUREAU OF RECLAMATION

Client: USACE-RMC & USBR-DSO
Project: Binders in Filter Material
Project No: BINDR **Figure** B-15

Tested By: B. Jackson **Checked By:** R. Rinehart

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	14.2	54.2	28.9	2.7	

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0	95.0 - 100.0	
#8	91.0	80.0 - 100.0	
#16	65.0	50.0 - 85.0	
#30	43.0	25.0 - 60.0	
#50	21.0	10.0 - 30.0	
#100	8.0	2.0 - 10.0	
#200	2.7		

* ASTM C 33 - Sand

Material Description

SP - POORLY GRADED SAND

Atterberg Limits

PL= NP LL= NV PI= NP

Coefficients

D_{90}= 2.2772 D_{85}= 1.9549 D_{60}= 1.0266
D_{50}= 0.7512 D_{30}= 0.4044 D_{15}= 0.2329
D_{10}= 0.1749 C_u= 5.87 C_c= 0.91

Classification

USCS= SP AASHTO= A-1-b

Remarks

Partially manufactured material containing about 20-30% crushed material. Fines assumed to be non-plastic.

Location: Oniell/Hooker Creek, Glacieal outwash (Ochoco Dam), Oregon
Sample Number: 71Z-10 (2011) **Date:** 7/25/2011

BUREAU OF RECLAMATION

Client: USACE-RMC & USBR-DSO
Project: Binders in Filter Material
Project No: BINDR **Figure** B-16

Tested By: B. Jackson **Checked By:** R. Rinehart

APPENDIX C

MSCT Results

Colorado Silica 36F-1136

Unit Wts (pcf)	Failure Time	Comments
112.2	6m-59s	splitting failure, saturated
111.9	7m-17s	ugly sample, perfect failure
112.0	1m-16s	splitting failure, unsaturated
111.5	1m-26s	splitting failure, saturated

Basalt Hill 36F-1137

Unit Wts (pcf)	Failure Time	Comments
119.5	24m-25s	
120.6	23m-44s	
119.6	27m-52s	
121.3	21m-20s	

Teichert 36F-1138

Unit Wts (pcf)	Failure Time	Comments
122.4	45m-1s	saturated
122.1	33m-52s	unsaturated
123.0	32m-03s	unsaturated

CEMEX 36F-1139

Unit Wts (pcf)	Failure Time	Comments
113.9	6m-21s	Many tests completed, highly variable
114.1	9m-24s	data

Triangle Rock 36F-1140

Unit Wts (pcf)	Failure Time	Comments
113.1	25m-13s	toppling failure, saturated
113.7	25m-2s	toppling failure, unsaturated
114.4	29m-46s	saturated

Granite Rock 36F-1141

Unit Wts (pcf)	Failure Time	Comments
117.1	23m-00s	
116.0	20m-55s	
117.9	22m-52s	
116.8	20m-46s	

Recycled Concrete 71Z-1

Unit Wts (pcf)	Failure Time	Comments
95.7		*no failure for any sample*
96.3		*all submerged overnight*
96.5		
96.3		

Ochoco 71Z-2

Unit Wts (pcf)	Failure Time	Comments
109.4	9m-49s	toppling failure, saturated
109.4	7m-02s	saturated
109.4	5m-25s	toppling failure, saturated
110.5	7m-43s	saturated

Lone Pine 71Z-3

Unit Wts (pcf)	Failure Time	Comments
111.9	10m-0s	
111.6	6m-19s	
112.8	11m-34s	
112.5	9m-12s	

Shevlin 71Z-4

Unit Wts (pcf)	Failure Time	Comments
113.6	32m-0s	Many tests completed, highly variable
112.4	24m-30s	data

Grizzly Rock 71Z-5

Unit Wts (pcf)	Failure Time	Comments
109.0	18m-29s	
109.9	17m-36s	
109.0	16m-53s	

Rock Products 71Z-6

Unit Wts (pcf)	Failure Time	Comments
105.4	18m-29s	
105.3	20m-58s	
105.8	21m-35s	

CEMEX Silica 71Z-7

Unit Wts (pcf)	Failure Time	Comments
111.8	0m-58s	toppling failure, saturated
112.4	1m-32s	
113.0	1m-13s	toppling failure, unsaturated
112.8	1m-22s	

Florida CEMEX Limestone 71Z-8

Unit Wts (pcf)	Failure Time	Comments
111.6	100m-30s	
110.2	100m-20s	
110.3	100m-17s	
109.7	100m-40s	

Stewart Silica 71Z-9

Unit Wts (pcf)	Failure Time	Comments
120.1	1m-1s	collapsed, unsaturated
119.5	0m-57s	collapsed, unsaturated
118.2	1m-50s	collapsed, saturated
119.1	3m-53s	

Oniell 71Z-10

Unit Wts (pcf)	Failure Time	Comments
116.2	20m-31s	
118.1	20m-48s	
117.1	23m-58s	

APPENDIX D

UCS Results

Colorado Silica 36F-1136

Unit Wts (pcf)	Peak Stress (psi)	Comments
110.9	2.21	
110.8	1.53	

Basalt Hill 36F-1137

Unit Wts (pcf)	Peak Stress (psi)	Comments
124.8	15.4	
123.5	19.04	
123.4	14.47	

Teichert 36F-1138

Unit Wts (pcf)	Peak Stress (psi)	Comments
121.9	36.46	
122.4	29.36	This sample had broke at the 1st lift line
122.8	47.49	

CEMEX 36F-1139

Unit Wts (pcf)	Peak Stress (psi)	Comments
115.4	12.1	
115.5	10.23	
115.2	7	

Triangle Rock 36F-1140

Unit Wts (pcf)	Peak Stress (psi)	Comments
111.0	10.53	
112.3	11.82	
111.2	9.74	

Granite Rock 36F-1141

Unit Wts (pcf)	Peak Stress (psi)	Comments
114.8	3.98	
115.7	11.33	
116.5	9.23	

Recycled Concrete 71Z-1

Unit Wts (pcf)	Peak Stress (psi)	Comments
96.2	5.73	
96.6	7.15	
95.7	2.89	
96.0	3.43	
95.9	3.46	

Ochoco 71Z-2

Unit Wts (pcf)	Peak Stress (psi)	Comments
109.7	6.27	
109.5	7.76	

Lone Pine 71Z-3

Unit Wts (pcf)	Peak Stress (psi)	Comments
114.8	4.26	
114.3	3.71	
115.2	5.13	Specimen broke at 1st lift line

Shevlin 71Z-4

Unit Wts (pcf)	Peak Stress (psi)	Comments
113.0	23.77	
113.5	25.61	
112.5	25.74	

Grizzly Rock 71Z-5

Unit Wts (pcf)	Peak Stress (psi)	Comments
104.8	5.06	Several samples crumbled with
104.5	3.51	handling

Rock Products 71Z-6

Unit Wts (pcf)	Peak Stress (psi)	Comments
108.6	7.77	
108.7	7.3	
109.8	6.86	

CEMEX Silica 71Z-7

Unit Wts (pcf)	Peak Stress (psi)	Comments
NA	0.81	
108.7	0.15	

Florida CEMEX Limestone 71Z-8

Unit Wts (pcf)	Peak Stress (psi)	Comments
111.5	31.4	
110.6	28.4	
112.8	44.5	

Stewart Silica 71Z-9

Unit Wts (pcf)	Peak Stress (psi)	Comments
113.7	2.15	
117.0	1.66	No post test photo
113.6	1.8	

Oniell 71Z-10

Unit Wts (pcf)	Peak Stress (psi)	Comments
119.0	9.83	
118.2	6.74	
118.8	11.62	

APPENDIX E

Sand Equivalent Test Reports

ASTM D 2419

Standard Test Method of Sand Equivalent Value of Soils and Fine Aggregate

Sample Identification 36F-1138 (Teichert)	Clay Reading	Sand Reading	Sand Equivalent	Actual Sand Equivalent
Test 1	5.3	14.2	79.2	80
Test 2	5.4	14.3	79.6	80
Test 3	5.3	14.2	79.2	80
Sample Average				80

Sample Identification 36F-1139 (CEMEX)	Clay Reading	Sand Reading	Sand Equivalent	Actual Sand Equivalent
Test 1	5.5	14.3	78.2	79
Test 2	5.5	14.2	76.4	77
Test 2	5.5	14.2	76.4	77
Sample Average				78

Sample Identification 36F-1140 (Triangle Rock)	Clay Reading	Sand Reading	Sand Equivalent	Actual Sand Equivalent
Test 1	5.7	14.3	75.4	76
Test 2	5.6	14.3	76.8	77
Test 3	5.9	14.4	74.6	75
Sample Average				76

Sample Identification 36F-1141 (Granite)	Clay Reading	Sand Reading	Sand Equivalent	Actual Sand Equivalent
Test 1	4.5	14.3	95.6	96
Test 2	4.4	14.3	97.7	98
Test 3	4.5	14.2	93.3	94
Sample Average				96

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ASTM D 2419

Standard Test Method of Sand Equivalent Value of Soils and Fine Aggregate

Sample Identification: 71Z-9 (Stewart Silica)	Clay Reading	Sand Reading	Sand Equivalent	Actual Sand Equivalent
Test 1	4.7	14.5	95.7	96
Test 2	4.7	14.5	95.7	96
Test 3	4.7	14.4	93.6	94
Sample Average				96

Sample Identification: 71Z-10 (Oneill)	Clay Reading	Sand Reading	Sand Equivalent	Actual Sand Equivalent
Test 1	4.6	14.2	91.3	92
Test 2	4.6	14.3	93.5	94
Test 2	4.8	14.3	89.6	90
Sample Average				92

Sample Identification: 36F-1136 (Colorado Silica)	Clay Reading	Sand Reading	Sand Equivalent	Actual Sand Equivalent
Test 1	4.6	14.4	95.7	96
Test 2	4.8	14.5	93.8	94
Test 3	4.7	14.4	93.6	94
Sample Average				95

Sample Identification: 36F-1137 (Basalt Hill)	Clay Reading	Sand Reading	Sand Equivalent	Actual Sand Equivalent
Test 1	7.5	14.0	53.3	54
Test 2	7.9	14.2	53.2	54
Test 3	7.8	14.0	51.3	52
Sample Average				54

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ASTM D 2419

Standard Test Method of Sand Equivalent Value of Soils and Fine Aggregate

Sample Identification 71Z-5 (Grizzly Products)	Clay Reading	Sand Reading	Sand Equivalent	Actual Sand Equivalent
Test 1	4.9	14.4	89.8	90
Test 2	4.9	14.3	87.8	88
Test 3	4.9	14.3	87.8	88
Sample Average				89

Sample Identification 71Z-6 (Rock Products)	Clay Reading	Sand Reading	Sand Equivalent	Actual Sand Equivalent
Test 1	5.0	14.4	88.0	88
Test 2	4.9	14.5	91.8	92
Test 2	5.0	14.4	88.0	88
Sample Average				90

Sample Identification 71Z-7 (Florida Silica - CEMEX)	Clay Reading	Sand Reading	Sand Equivalent	Actual Sand Equivalent
Test 1	4.4	14.4	100.0	100
Test 2	4.4	14.4	100.0	100
Test 3	4.4	14.4	100.0	100
Sample Average				100

Sample Identification 71Z-8 (Florida Limestone - CEMEX)	Clay Reading	Sand Reading	Sand Equivalent	Actual Sand Equivalent
Test 1	4.7	14.6	97.9	98
Test 2	4.8	14.5	93.8	94
Test 3	4.7	14.3	91.5	92
Sample Average				95

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ASTM D 2419

Standard Test Method of Sand Equivalent Value of Soils and Fine Aggregate

Sample Identification 71Z-1 (Recycled Concrete)	Clay Reading	Sand Reading	Sand Equivalent	Actual Sand Equivalent
Test 1	5.0	14.5	90.0	90
Test 2	4.6	14.2	91.3	92
Test 3	4.7	14.4	93.6	94
Sample Average				92

Sample Identification 71Z-2 (Ochoco)	Clay Reading	Sand Reading	Sand Equivalent	Actual Sand Equivalent
Test 1	5.1	14.2	82.4	83
Test 2	5.0	14.0	80.0	80
Test 2	5.2	14.1	78.9	79
Sample Average				81

Sample Identification 71Z-3 (Lone Pine)	Clay Reading	Sand Reading	Sand Equivalent	Actual Sand Equivalent
Test 1	4.7	14.3	91.5	92
Test 2	4.9	14.2	85.7	86
Test 3	4.9	14.2	85.7	86
Sample Average				88

Sample Identification 71Z-4 (Shevlin)	Clay Reading	Sand Reading	Sand Equivalent	Actual Sand Equivalent
Test 1	4.9	14.4	89.8	90
Test 2	4.6	14.3	93.5	94
Test 3	4.8	14.3	89.6	90
Sample Average				92

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APPENDIX F

Petrographic Memo (MERL-2012-16)

United States Department of the Interior

BUREAU OF RECLAMATION
P.O. Box 25007
Denver, Colorado 80225-0007

IN REPLY REFER TO:

JUN 6 2012

To: Robert Rinehart
Civil Engineer, Materials Engineering Research Laboratory Group, Technical Service Center, 86-68180

From: Doug Hurcomb
Geologist, Materials Engineering and Research Laboratory Group, Technical Service Center, 86-68180

Subject: Petrographic Examination of Filter Binder Research Specimens – Dam Safety Office Research, Denver Colorado

Materials Engineering and Research Laboratory No. MERL 2012-16

Petrographic referral code: 2012-03

INTRODUCTION

Robert Rinehart submitted compacted cylinders fabricated from filter materials from various sources to the Petrographic Laboratory for examination. The filter materials are part of a program to research binding agents in embankment dam protective filters.

The submitted intact and collapsed cylinders were labeled Filter Binder Research. The filter material source, MERL-Geotech lab index numbers, and petrographic thin section numbers are as follows:

- Basalt Hill (crushed talus material), 36F-1137; P-12,291
- Colorado Silica Sand, 36F-1136; P-12,292
- Ochoco Dam Borrow, 71Z-2; P-12,293
- Shevlin Sand and Gravel; 71Z-4; P-12,294
- CEMEX Limestone Sand (FL), 71Z-8; P-12,295
- Recycled Concrete, 71Z-1; P-12,296

The compacted samples and their properties are described in Bureau of Reclamation report DSO-11-04, Binding Agents in Embankment Dam Protective Filters, Rinehart and Pabst, March 31, 2011, and a paper (in press) titled A Test for Cementation Potential of Granular Filter Material, Rinehart, Pabst, Ngozi-Bullock, and Jackson, 2012. The filter materials were processed to meet the gradation requirements of ASTM C33 for fine aggregates with the additional requirement of fines content less than 2 percent before compaction.

The purposes of the examinations were to petrographically illustrate fabric and grain-to-grain relations of the compacted sample fragments, identify any material acting as cement or binder, and provide a brief description of the grain-to-grain relations affected by any binder.

CONCLUSIONS

The Basalt Hill, Colorado Silica Sand, Ochoco Borrow, and Shevlin Sand specimens were weakly cemented with fine aggregate bonds and tap water residue. The difference in sample stability for the observed weakly cemented samples is likely controlled by the number of finer size rock and mineral aggregates located at grain contacts which increase the particle surface area at grain contacts. It is likely that the evaporation of Denver tap water contributed minute amounts of residue at grain contacts. Increasing the amount of fines between grains appears to stabilize the sample.

The sample stability of the more strongly cemented CEMEX and Recycled Concrete samples is likely controlled by the presence of numerous contact areas and gaps filled with calcium carbonate or carbonated Portland cement fines. Numerous calcium carbonate cemented contact areas filled CEMEX sample voids. Numerous carbonated Portland cement paste particles cemented contact areas and filled recycled concrete voids.

PETROGRAPHIC EXAMINATION AND DISCUSSION

The petrographic examination consisted of megascopic and microscopic observations, including Petrographic and Scanning Electron Microscope (SEM) and a few physical and chemical tests.

Polished petrographic thin sections of intact fragments were fabricated by David Mann, High Mesa Petrographics, Los Alamos NM. Intact fragments were stabilized in Los Alamos with blue-dye colored epoxy and the hardened epoxy impregnated fragment was cemented onto a glass slide, sectioned, and finely ground for viewing with both a petrographic microscope and SEM. The blue-dye did not penetrate all voids of the specimens and the epoxy occupying most voids is typically colorless. However, the colorless epoxy can be petrographically distinguished from grains by the presence of abrasive grit due to grinding and polishing and its optical properties. Epoxy appears black and the gray and white portions are rock and mineral fragments in the SEM images.

Elemental analyses of grain contact areas were provided by Energy Dispersive X-ray (EDS). EDS is an analytical technique used for elemental analysis in combination with the SEM. EDS detects x-rays emitted from the sample activated by the SEM electron beam. The electrons represent the composition of the sample surface. The sample x-ray energy values from the EDS spectrum are compared with known characteristic x-ray energy values to qualitatively determine the presence of an element in the sample.

The thin sections represent an unoriented, two-dimensional slice of the submitted specimen. Grain-to-grain relations may be referred to as concavo-convex contact, long contact, and/or point contact as described and illustrated in Pettijohn, Potter, and Siever's textbook, Sand and Sandstone, figure 3-10, pages 89 to 93, Springer-Verlag, 1972. Any grains which appear suspended in the epoxy matrix (floating grains) are likely in grain-to-grain contact above or below the plane of the thin section. Consolidation of sand imparts a degree of compactness or density on the samples which affects the sample fabric. The evidence for lithification by consolidation is the grain-to grain relationships including fines and the presence or absence of a binder. The following sketch illustrates the fabric terminology used in this report.

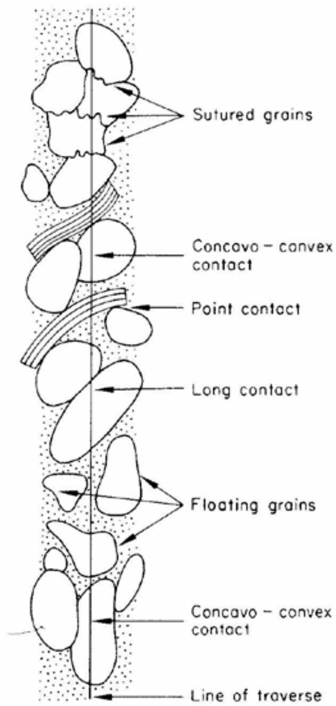

Fig. 3-10. Definition sketch of fabric terminology: quartz (white), mica (lined), and matrix (stippled)

(Illustration from Pettijohn, Potter, and Siever, 1972, Sand and Sandstone)

RESULTS

The results are presented in Table 1 and figures 1 to 37. The figures show low and high magnification images of the as-received sample surfaces, petrographic micrograph images in plain light, and backscattered electron images of the polished thin section surface. Any binder typically occupies the contact area between grains and is pointed out in the figure captions.

SUMMARY

The specimen containing Basalt Hill (figures 2 to 7) exhibits rock and mineral grains in chiefly point and long contact with a few concavo-convex contacts. The particles are angular and subangular in shape. Cursory petrographic examination indicates the rock and mineral grains were composed of chiefly basaltic rock with lesser and minor volcanic glass, pyroxene, olivine, and feldspar with a few miscellaneous mineral types. The grains are in direct contact with a fine particle bond binder present at some grain contacts.

The specimen containing Colorado Silica Sand (figures 8 to 14) exhibits mineral grains in chiefly point and long contact. The particles were chiefly subangular to rounded with a few angular in shape and moderately packed. Cursory petrographic examination indicates the mineral grains were composed of chiefly quartz and feldspar with a few miscellaneous minerals including mica, hornblende, and zircon. The grains are in direct contact with a fine particle bond binder present at some grain contacts.

The specimen containing Ochoco Borrow Sand (figures 15 to 20) exhibits rock and mineral grains in chiefly long contact with several concavo-convex and point contact. The fabric appears compact with apparent grain rearrangement and breakage due to compaction. The particles appear subrounded and rounded with a few subangular in shape with a few angular and moderately well packed. Cursory petrographic examination indicates the rock and mineral grains were composed of chiefly basaltic, altered and glassy volcanic rock types with minor pyroxenes, quartz, feldspar and a few miscellaneous minerals. Some grains appear strained or deformed by compaction. The grains are in direct contact with a fine particle bond binder present at some grain contacts.

The specimen containing Shevlin Sand and Gravel (figures 21 to 26) exhibits rock and mineral grains in chiefly long contact and point contact with several floating grains. The fabric appears compact with apparent rearrangement and densification due to compaction. The particles appear angular and subangular with a few subrounded in shape with a few angular and well packed. Cursory petrographic examination indicates the rock and mineral grains were composed of altered and glassy volcanics and volcanic glass with lesser and minor pyroxenes, quartz and feldspars and a few miscellaneous minerals The grains are in direct contact with a fine particle bond binder present at some grain contacts.

The specimen containing CEMEX Limestone (figures 27 to 32) exhibits rock and mineral grains in long and point contact. The particles are chiefly subangular and rounded with a few angular and rounded in shape. Calcium carbonate fills many grain contacts areas and acts as a binder between grains. Cursory petrographic examination indicates the rock and mineral grains were composed of limestone rock types and quartz grains with a few miscellaneous minerals. Individual grain contacts and gaps were cemented with apparent micro-crystalline, calcium carbonate cement.

The specimen containing Recycled Concrete (figures 33 to 37) exhibits concrete and concrete paste particles and sand-size aggregates including quartz, feldspar, mica, and amphiboles. The concrete particles were composed of Portland cement paste and embedded aggregates as well as ettringite occupying internal voids. The concrete fragments and mineral grains are in chiefly long contact with several point and very few concavo-convex and floating grains. The particles are subangular and subrounded in shape. Calcium carbonate grains fill gaps between the concrete material and acts like a binder. It is likely that calcium hydroxide (Portlandite) from the hydrated cement matrix was leached out of the cement during sample processing. Calcium hydroxide then reacted with carbon dioxide from the atmosphere to form calcium carbonate.

RECOMMENDATIONS FOR FUTURE WORK

Conduct X-ray diffraction analyses of any residual fines in the compacted sand to identify minerals present. Conduct analyses of the water used for wetting during compaction and determine the mineralogical composition of any mineral residue of the pore water.

Attachments

cc: 86-6818 (Hurcomb, Ngozi-Bullock, Jackson, and petro copy)

WBR:DHurcomb:glopez:06/06/2012:303-445-2336

(H:\D8180\MERL Reports\2012\MERL-2012-16 Petro exam of filter binder\Filter Binder Reseach 6-4-12 (2).docx)

Table 1. Filter Binder Research Summary. The examined specimens were unstressed cylinder fragments.		
Sample	Grain shape	Contact; binder type
Basalt Hill	Angular and subangular	Point grain contact; fine particle bonds
Colorado Silica Sand	Subangular to rounded	Point and long grain contacts; fine particle bonds
Ochoco Borrow	Subrounded and rounded	Point and long grain contacts; fine particle bonds
Shevlin Sand	Subangular and subrounded	Long, concavo-convex, and a few point grain contacts; fine particle bonds
CEMEX	Subanguar and subrounded	Chiefly long contact with a few point; calcium carbonate filled contacts and gaps
Recycled Concrete	Subangular and subrounded	Long, concavo-convex and point contacts; carbonated concrete paste

Figure 1. The image shows the submitted filter binder research cylinders after removing material for thin section preparation. Note: Some of the samples completely disaggregated and some are essentially intact after handling.

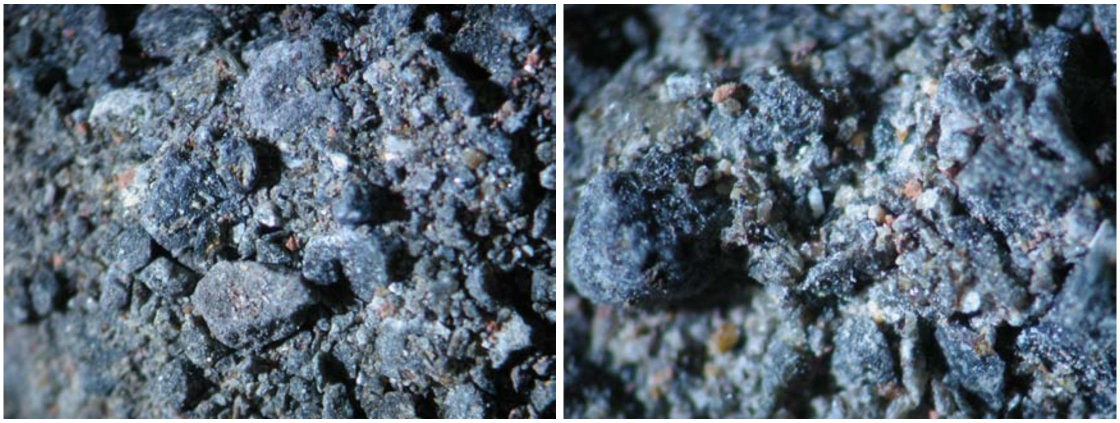

Figure 2. Basalt Hill (talus material), 36F-1137. The images show the irregular surfaces of as-received specimen fragments at two different magnifications. The particles are angular and subangular in shape. The field on the left image is about 16 mm width and the field on the right is 6 mm width and the corresponding magnifications are about 6X and 17X, respectively.

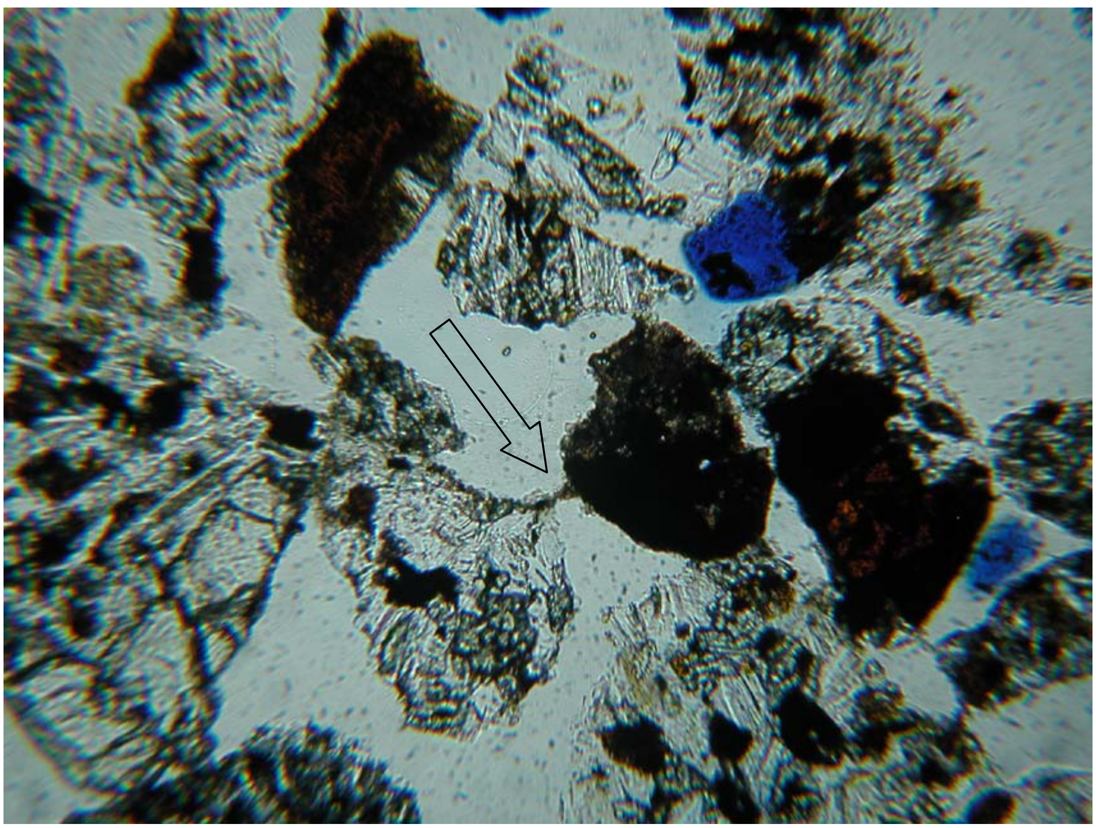

Figure 3. Basalt Hill (crushed talus material), 36F-1137, Thin Section P-12-961. The image shows typical grain relationships including point and long contacts with a few concavo-convex and an apparent fine particle bridge in the center of the image (arrow). The rock and mineral grains appear angular and subangular in shape. The area occupied by the arrow is void space filled by epoxy material. The field width of the image is about 1.2 mm with a magnification of about 170X.

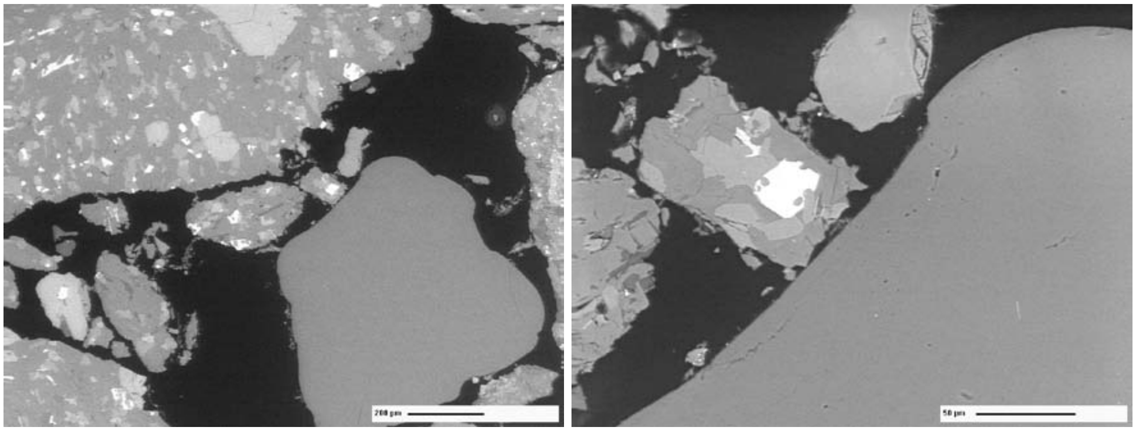

Figure 4. Basalt Hill (crushed talus material), 36F-1137, Thin Section P-12-961. The grains are in point contact. Direct contact between grains or contact by fine grain aggregates appears to form a binder. The magnification is 100 and 500X with bar scales of 200 µm (left) and 50 µm (right), respectively.

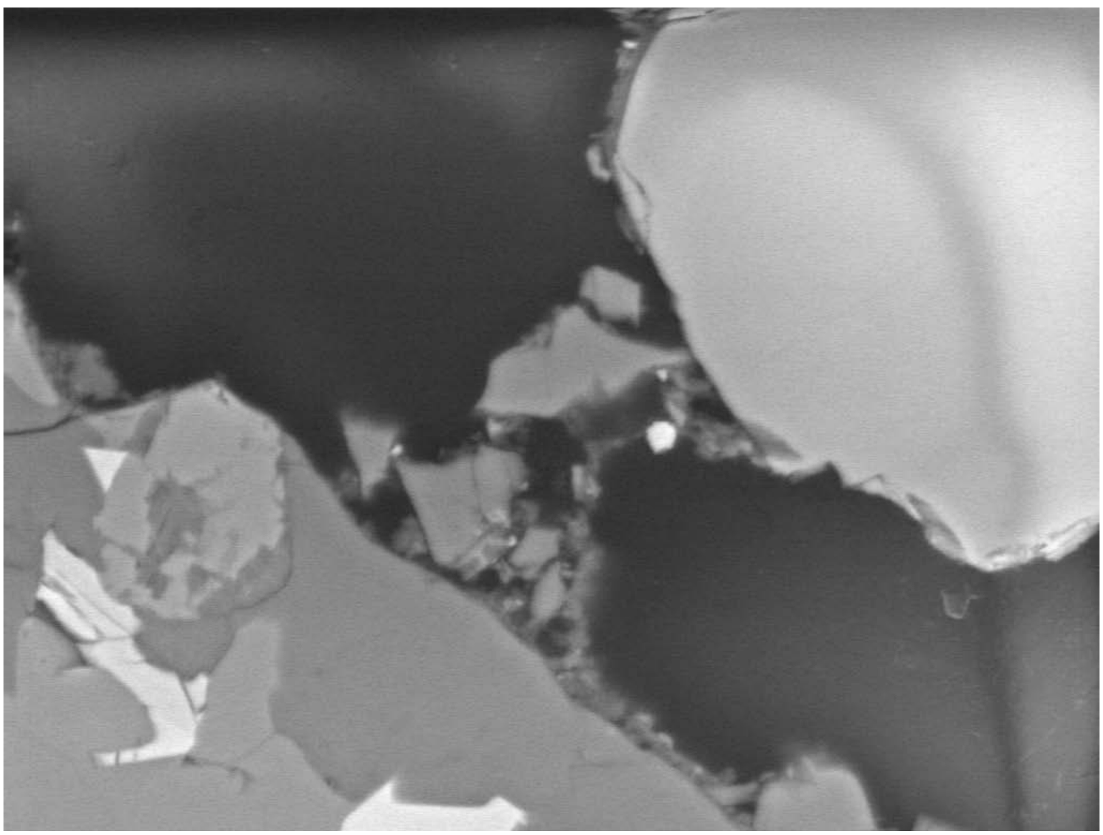

Figure 5. The higher magnification image shows fine particle bonds bridging grain contacts in figure 4. The image was acquired at a magnification of 2000X; a scale marker is not available.

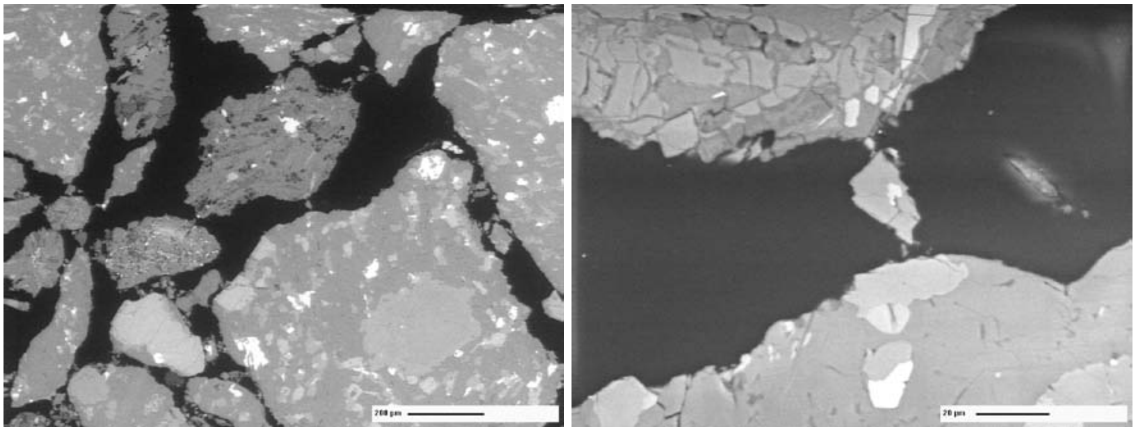

Figure 6. Basalt Hill (talus material), 36F-1137, Thin Section P-12-961. The grains are in point contact with fines bridging gaps between sand-size particles. Direct contact between grains or contact by fine grain aggregates appears to form a binder. The magnification is 100 and 1000X with bar scales of 200 µm (left) and 20 µm (right), respectively.

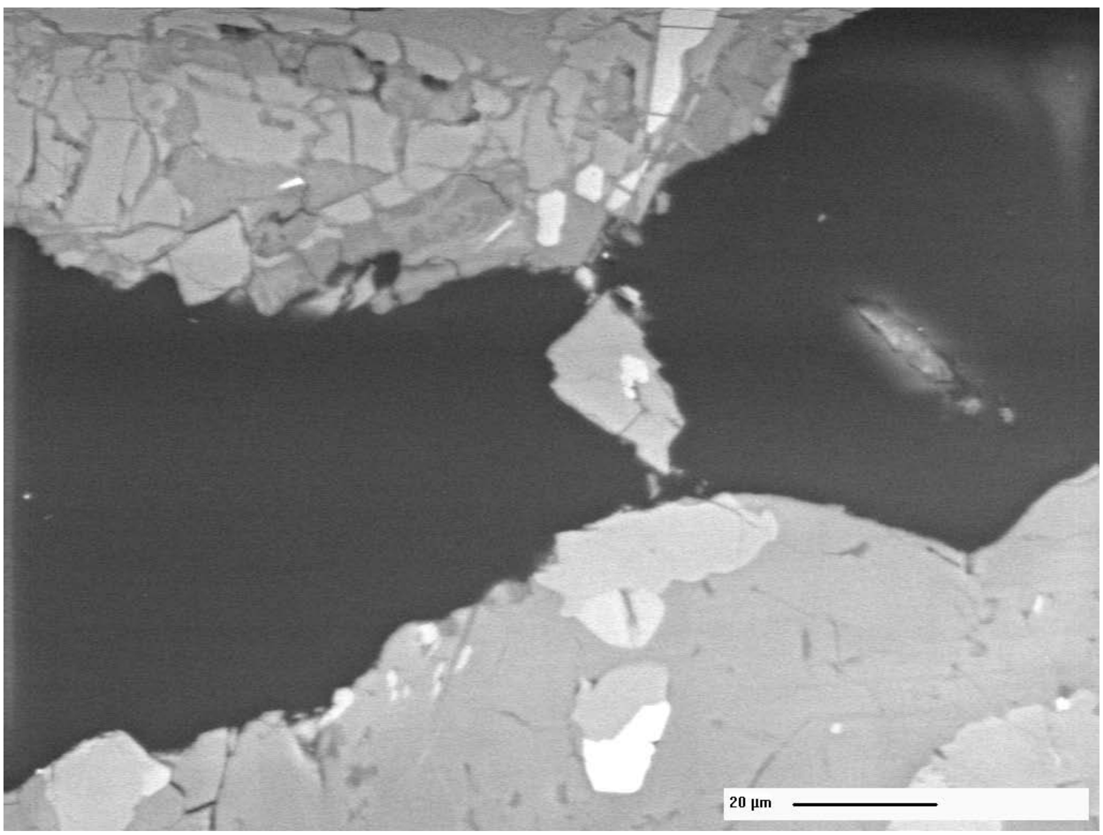

Figure 7. The higher magnification image shows fine particle bonds bridging grain contacts in figure 6. The image was acquired at a magnification of 1000X; the scale marker is 20 µm.

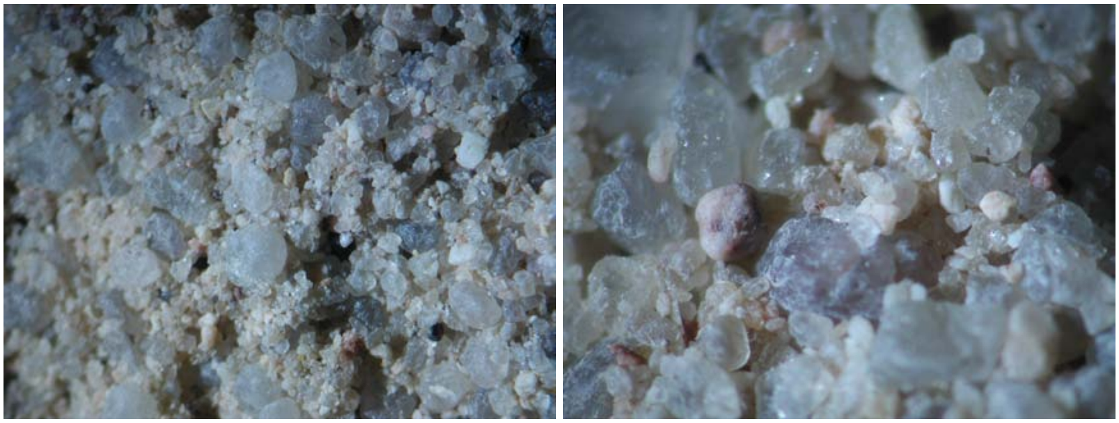

Figure 8. Colorado Silica Sand, 36F-1136. The images show the irregular surfaces of as-received specimen fragments at two different magnifications. The particles are subangular to rounded in shape. The field on the left image is about 16 mm width and the field on the right is 6 mm width and the corresponding magnifications are about 6X and 17X, respectively.

Figure 9. Colorado Silica Sand, 36F-1136, Thin Section P-12,292. The image shows typical grain relationships including point (white arrows) and long contacts (black arrow). The quartz and feldspar grains appear subangular to rounded with a few angular in shape and moderately packed. The area between grains is void space filled by epoxy material. The field width of the image is about 1.2 mm with a magnification of about 170X.

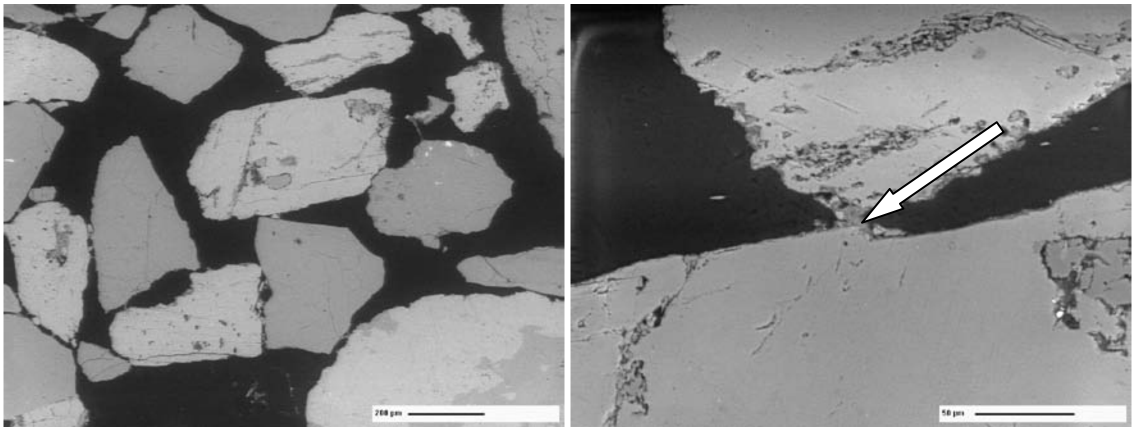

Figure 10. Colorado Silica Sand, 36F-1136, Thin Section P-12,292. The grains are in long and point contact with fine particles between some sand-size particles (arrow). The magnification is 100 and 500X with bar scales of 200 µm (left) and 50 µm (right), respectively.

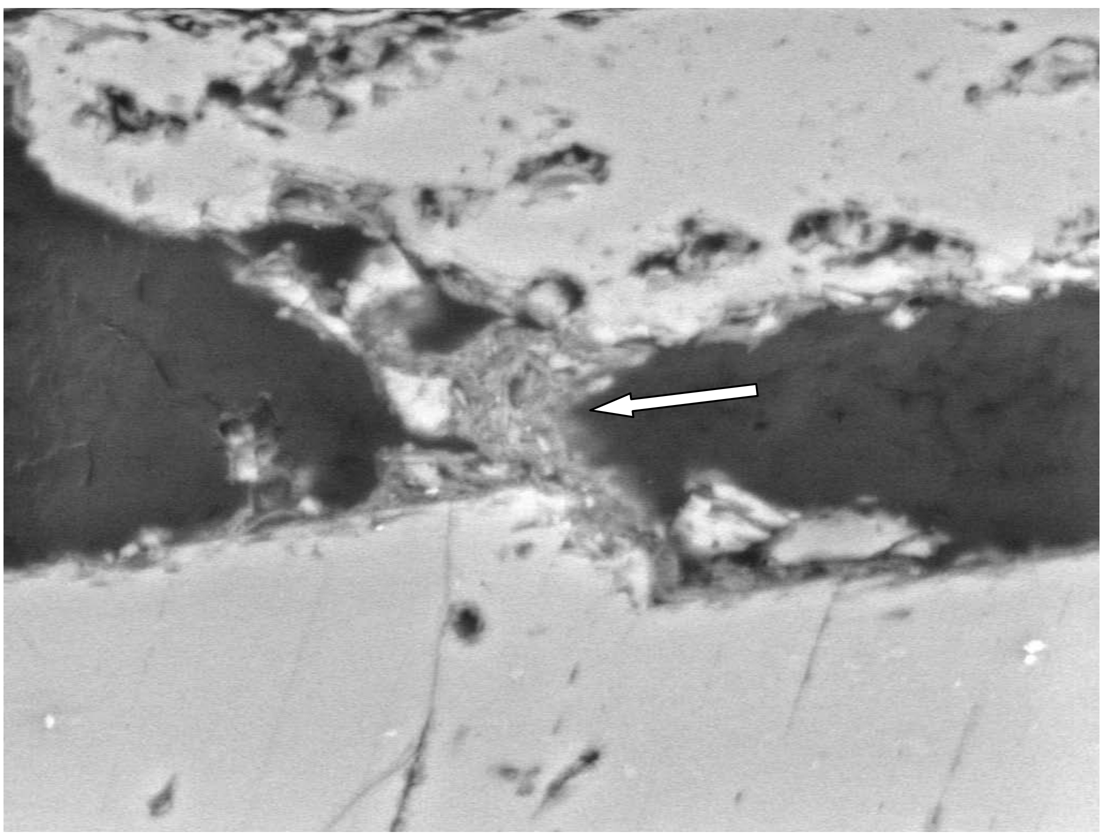

Figure 11. The higher magnification image shows fine particle bonds at grain contacts in figure 10. The image was acquired at a magnification of 2000X; a scale marker is not available.

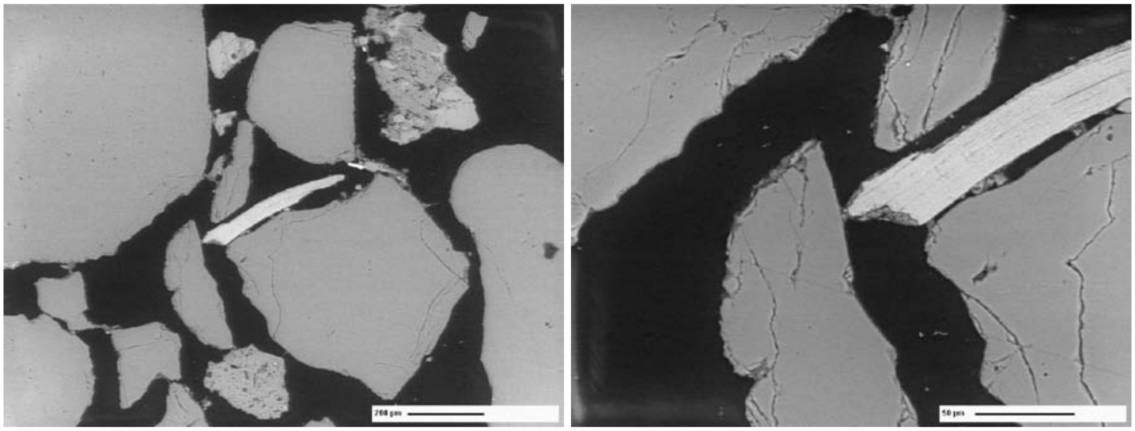

Figure 12. Colorado Silica Sand, 36F-1136, Thin Section P-12,292. The grains are in long and point contact. The magnification is 100 and 500X with bar scales of 200 µm (left) and 50 µm (right), respectively.

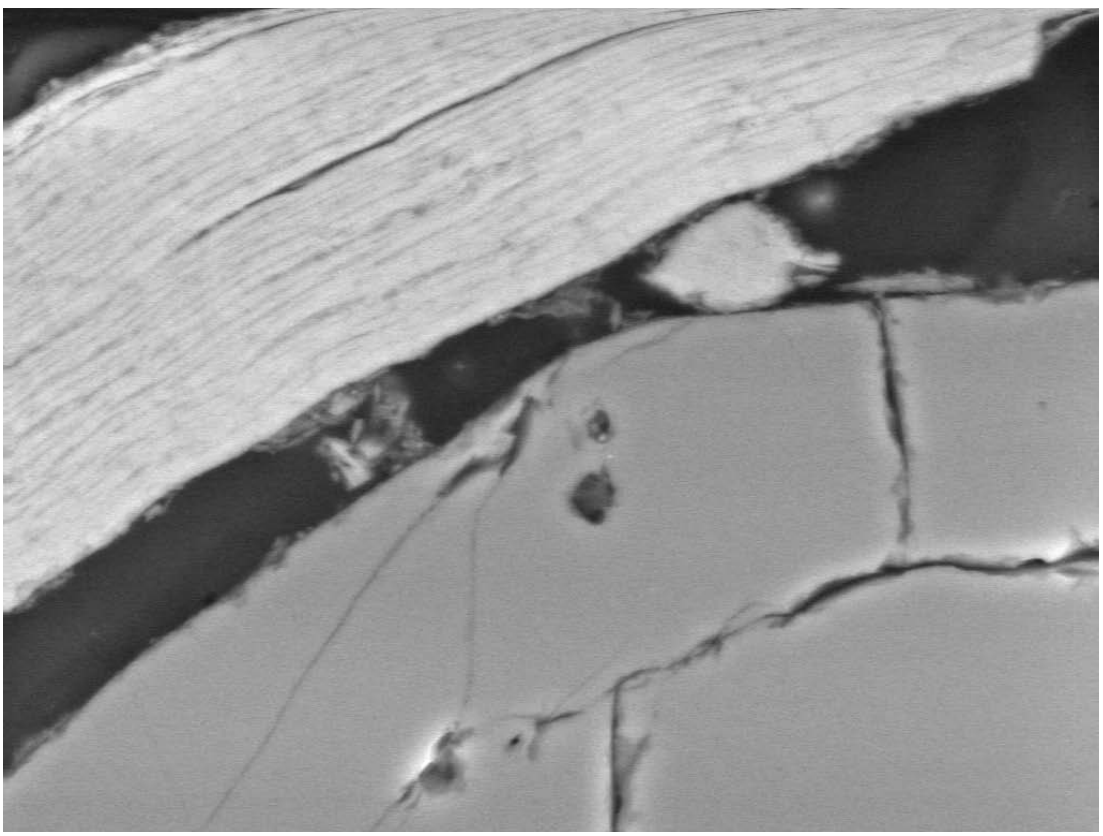

Figure 13. The higher magnification image shows fine particle bonds at grain contacts in figure 12. The image was acquired at a magnification of 2000X; a scale marker is not available.

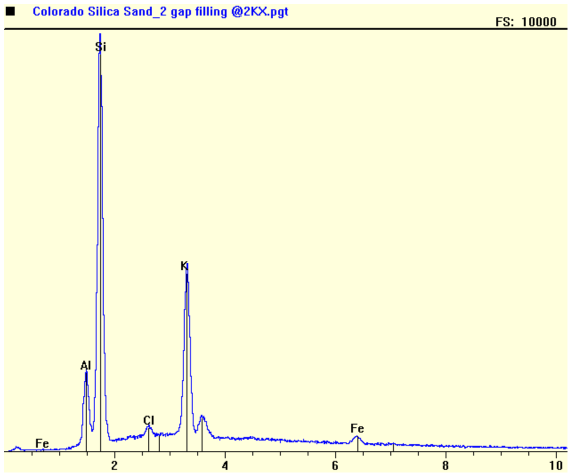

Figure 14. Energy Dispersive X-ray analysis indicates gap filling material in figure 11 (arrow) is likely rock and mineral particles and mineral residue from Denver tap water. The graph show intensity on the vertical axis and the x-ray energy on the horizontal axis.

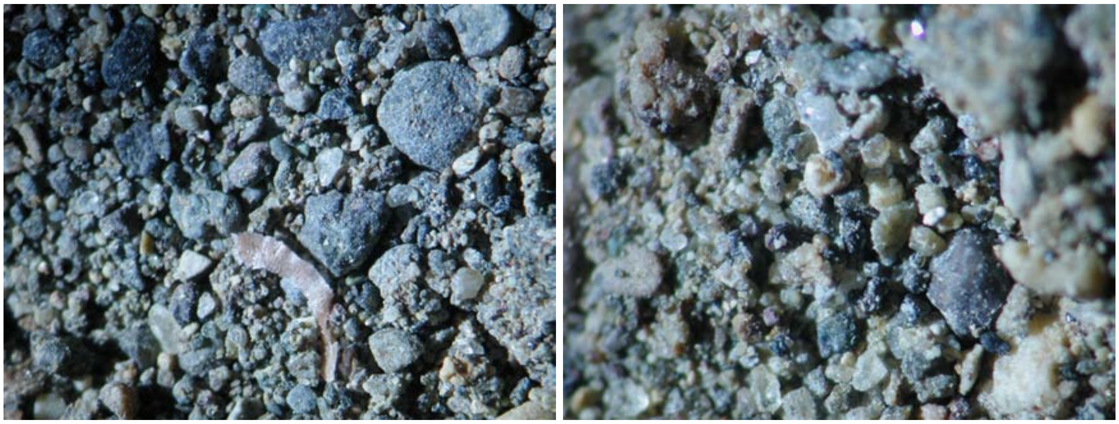

Figure 15. Ochoco Dam Borrow, 71Z-2. The images show the irregular surfaces of as-received specimen fragments at two different magnifications. The particles are subrounded and rounded with a few subangular in shape. The field on the left image is about 16 mm width and the field on the right is 6 mm width and the corresponding magnification are about 6X and 17X, respectively.

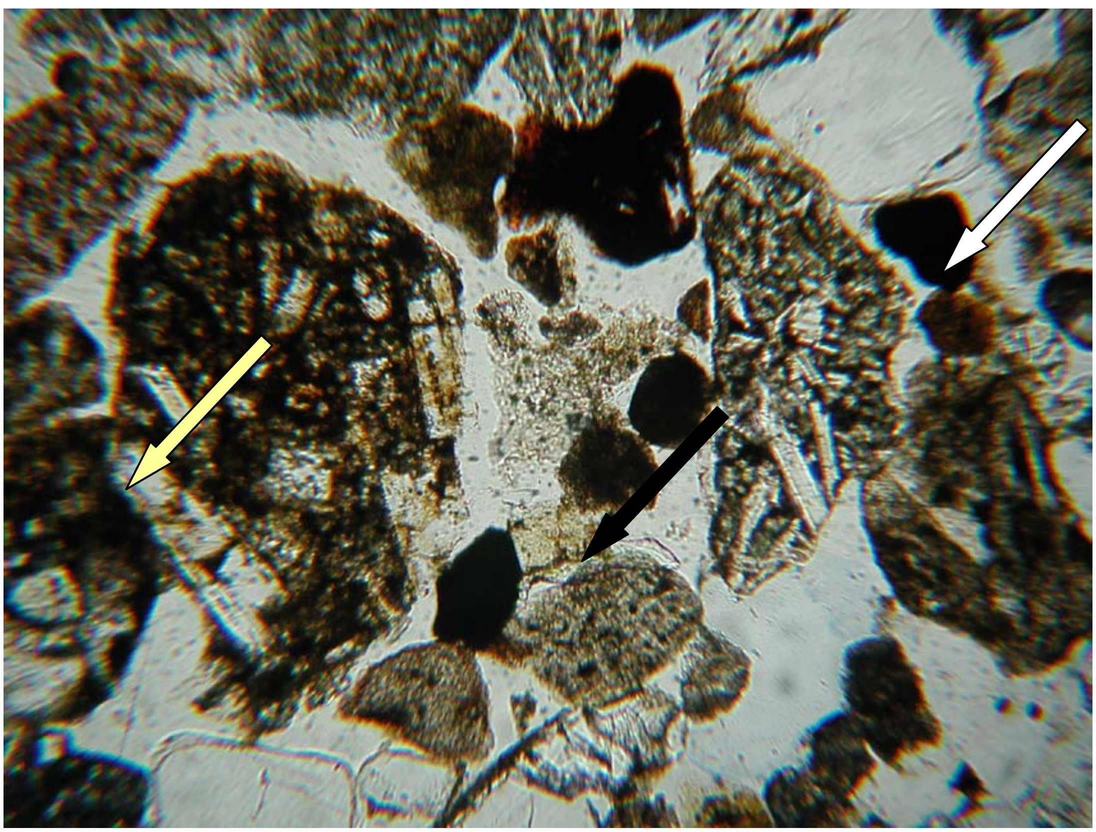

Figure 16. Ochoco Dam Borrow, 71Z-2, Thin Section P-12,293. The image shows typical grain relationships including chiefly long (black arrow) with a few point (white arrows) and concavo-convex contacts (yellow arrows). The fabric appears compact with apparent grain rearrangement due to compaction. The rock and mineral grains appear subrounded and rounded with a few subangular in shape and moderately well packed. The area between grains is void space filled by epoxy material. The field width of the image is about 1.2 mm with a magnification of about 170X.

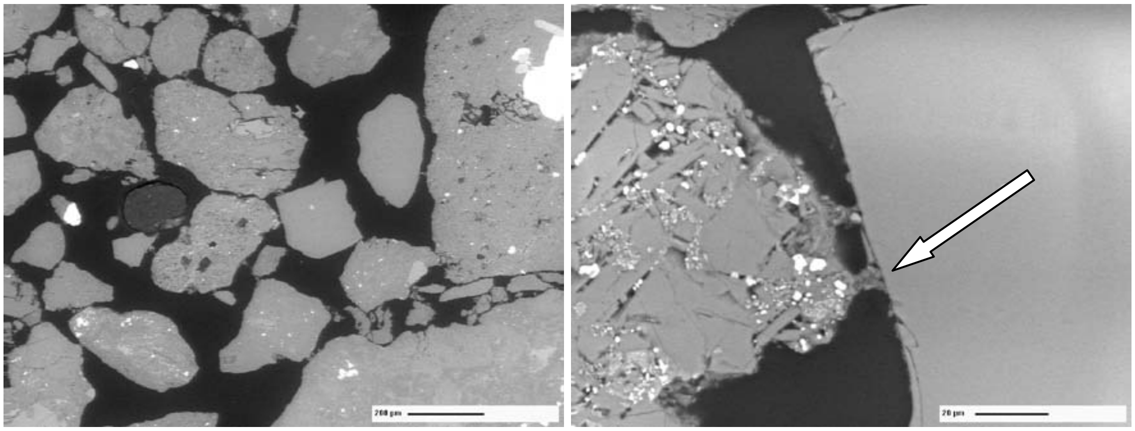

Figure 17. Ochoco Dam Borrow, 71Z-2 Thin Section P-12,293. The grains are in long and point contact. A binder is present at few grain contacts (arrow). The magnification is 100 and 1000X with bar scales of 200 µm (left) and 20 µm (right), respectively.

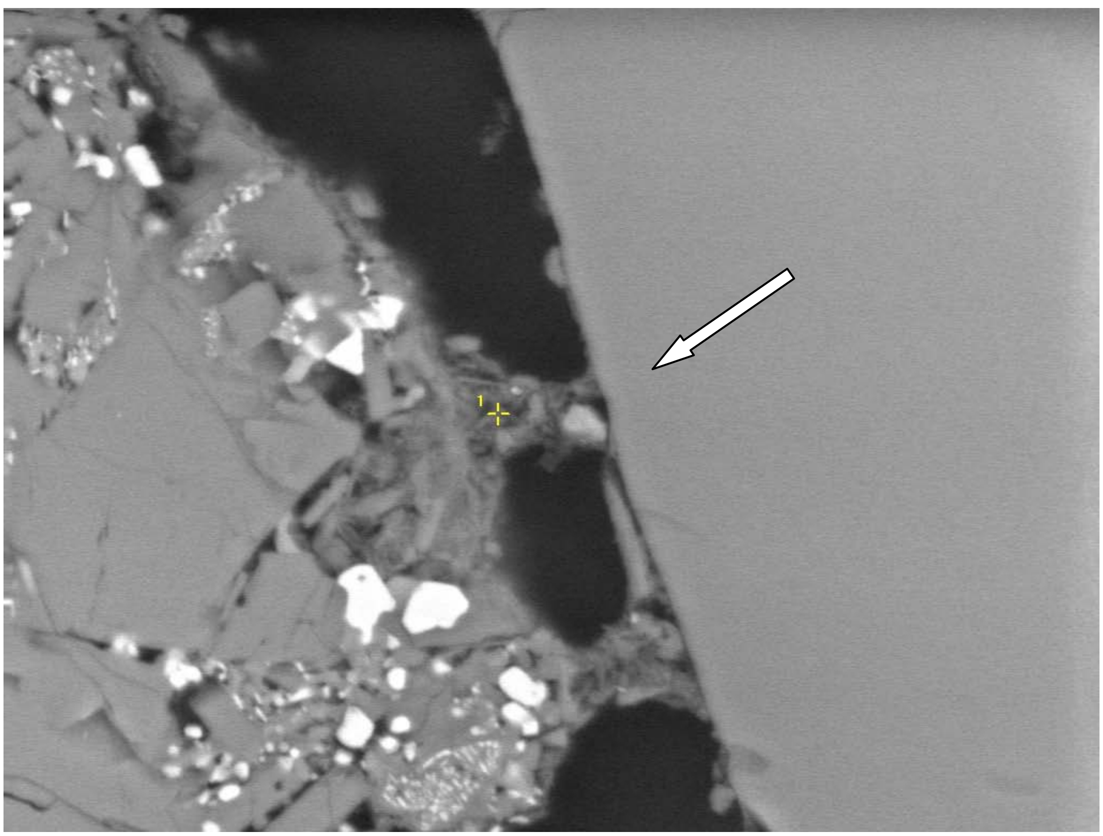

Figure 18. The higher magnification image shows fine particle bonds at grain contacts in figure 17. The image was acquired at a magnification of 2000X; a scale marker is not available.

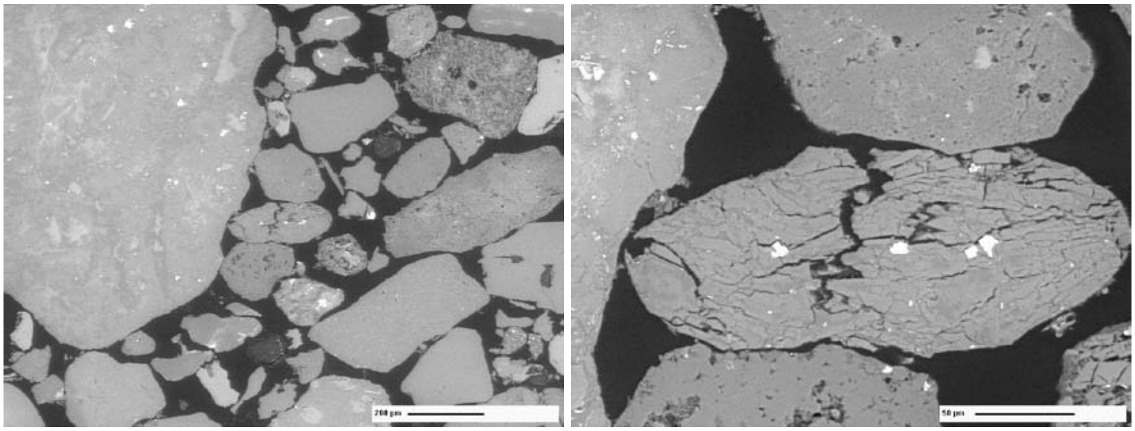

Figure 19. Ochoco Dam Borrow, 71Z-2 Thin Section P-12,293. The images provide evidence for grain deformation. The grains are in long and point contact with some gaps filled with fines. The magnification is 100 and 500X with bar scales of 200 µm (left) and 50 µm (right), respectively.

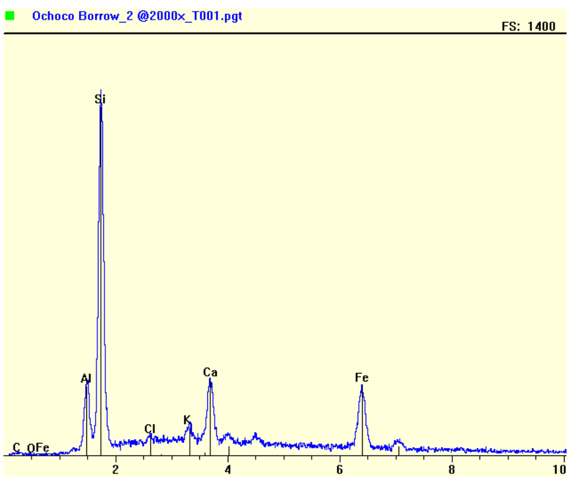

Figure 20. Energy Dispersive X-ray analysis indicates gap filling material in figure 18 (arrow and yellow marker) is likely rock and mineral particles and mineral residue from Denver tap water. The graph shows intensity on the vertical axis and the x-ray energy on the horizontal axis.

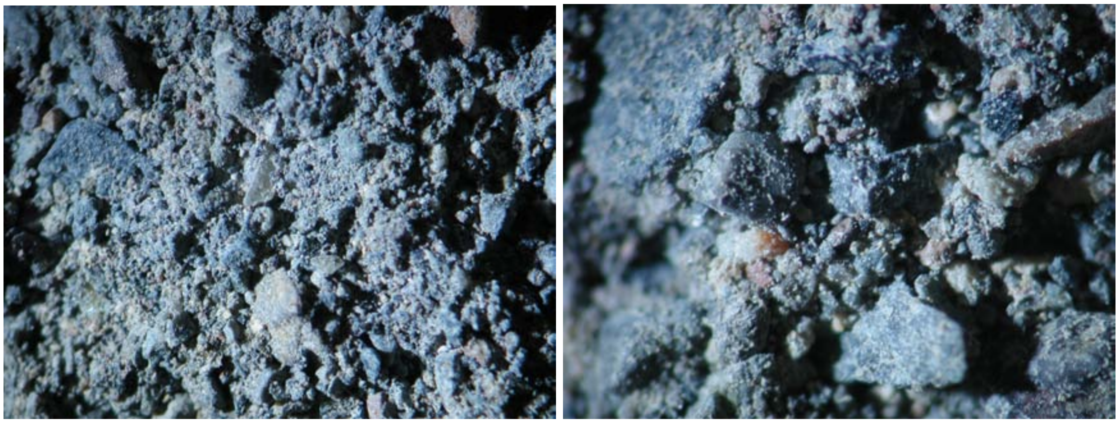

Figure 21. Shevlin Sand and Gravel, 71Z-4. The images show the irregular surfaces of as-received specimen fragments at two different magnifications. The particles appear angular and subangular in shape. The field on the left image is about 16 mm width and the field on the right is 6 mm width and the corresponding magnification are about 6X and 17X, respectively.

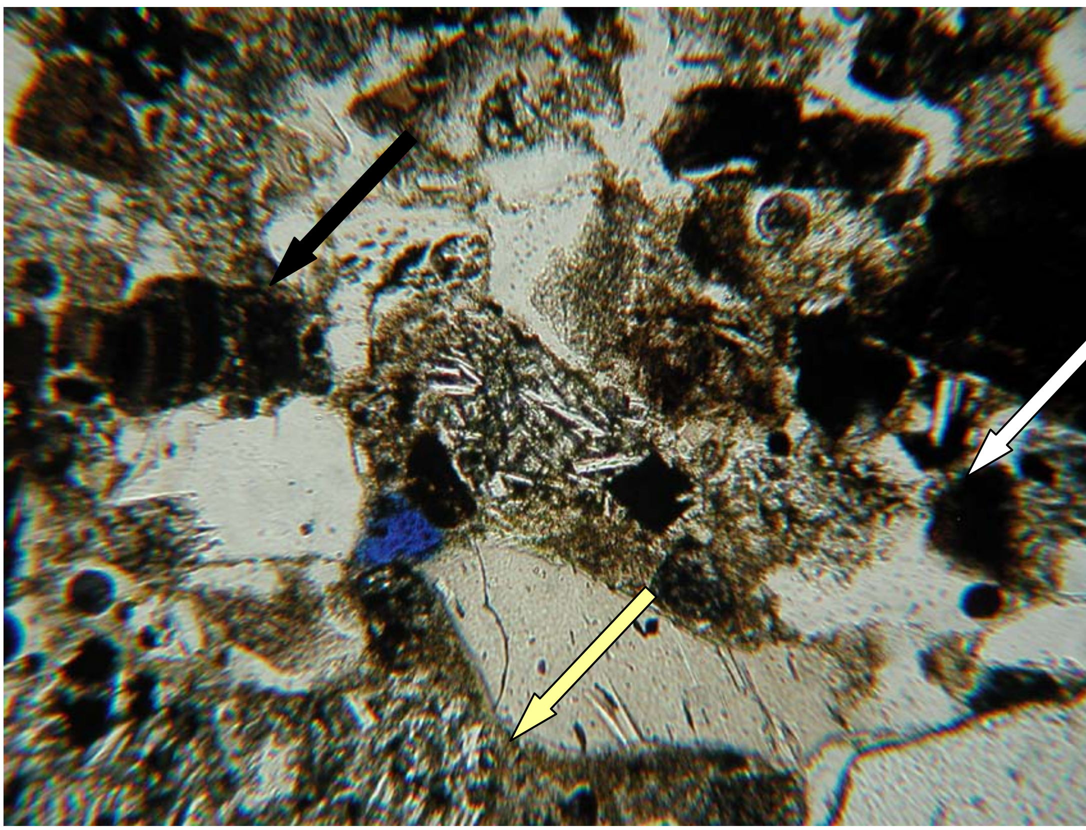

Figure 22. Shevlin Sand and Gravel, 71Z-4, Thin Section P-12,294. The image shows typical grain relationships including long (black arrow) and concavo-convex contacts (yellow arrows) with few point (white arrows) and a paucity of voids. The fabric appears compact with apparent rearrangement and densification due to compaction. The rock and mineral grains appear angular and subangular with a few subrounded in shape and well packed. The area between grains is void space filled by epoxy material and fines. The field width of the image is about 1.2 mm with a magnification of about 170X.

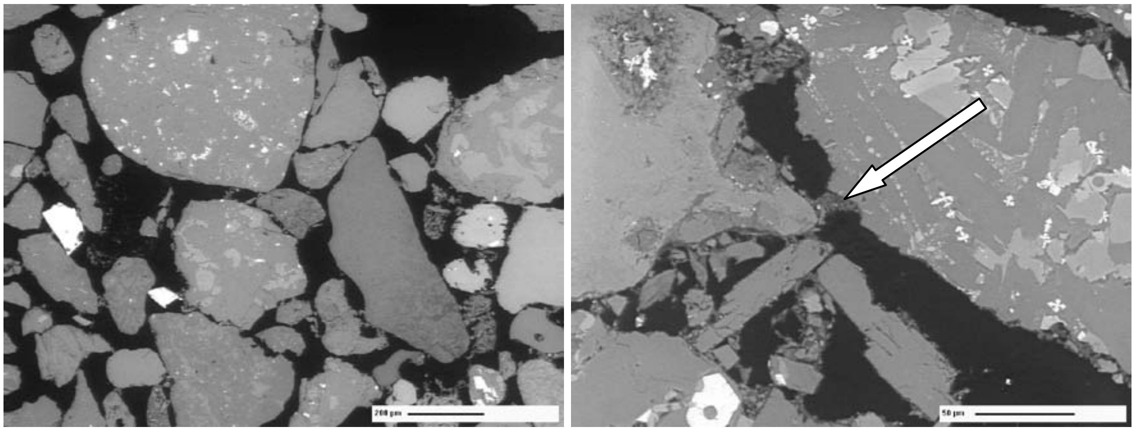

Figure 23. Shevlin Sand and Gravel, 71Z-4, Thin Section P-12,294. The grains are chiefly in long contact with few in point contact. Several contact areas and gaps are filled with finer aggregates (arrow). Many voids and gaps are filled with fines increasing the surface area of grain contacts. Higher magnification images indicate the material filling the gap is silt and clay size aggregates. The magnification is 100 and 500X with bar scales of 200 µm (left) and 50 µm (right), respectively.

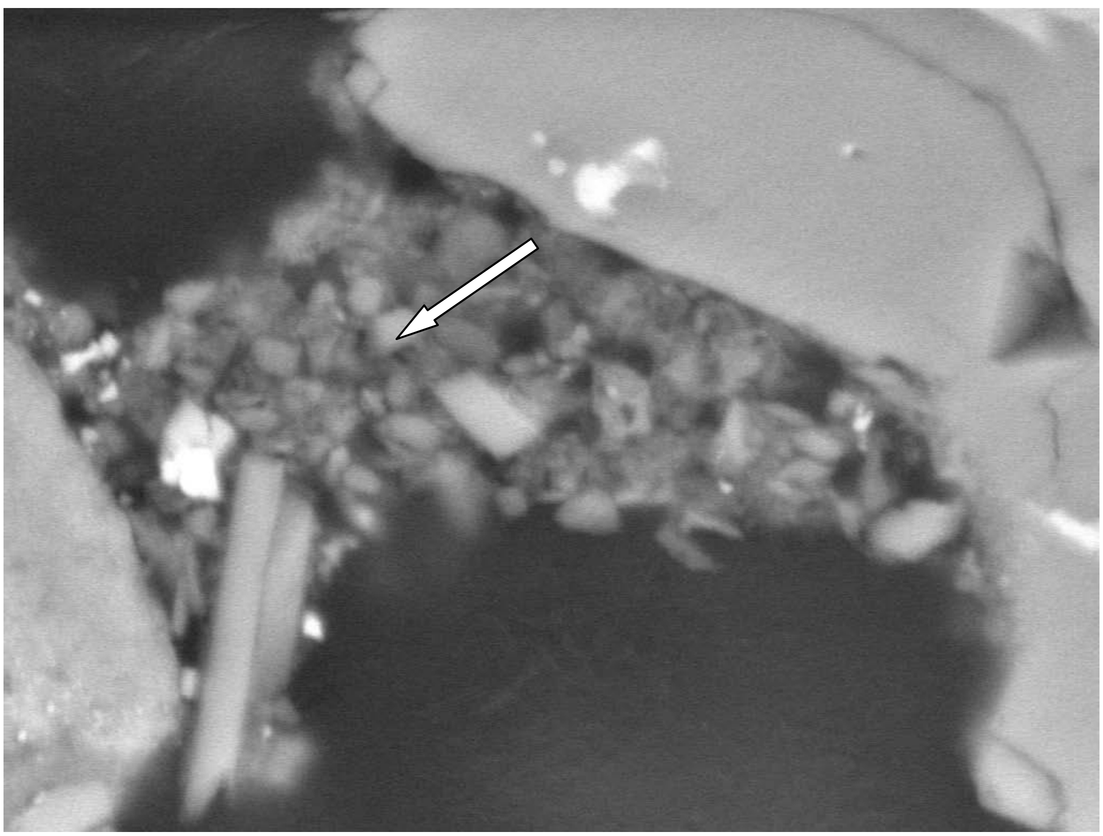

Figure 24. The higher magnification image shows fine particle bonds bridging grain contacts in figure 23. The image was acquired at a magnification of 5000X; a scale marker is not available.

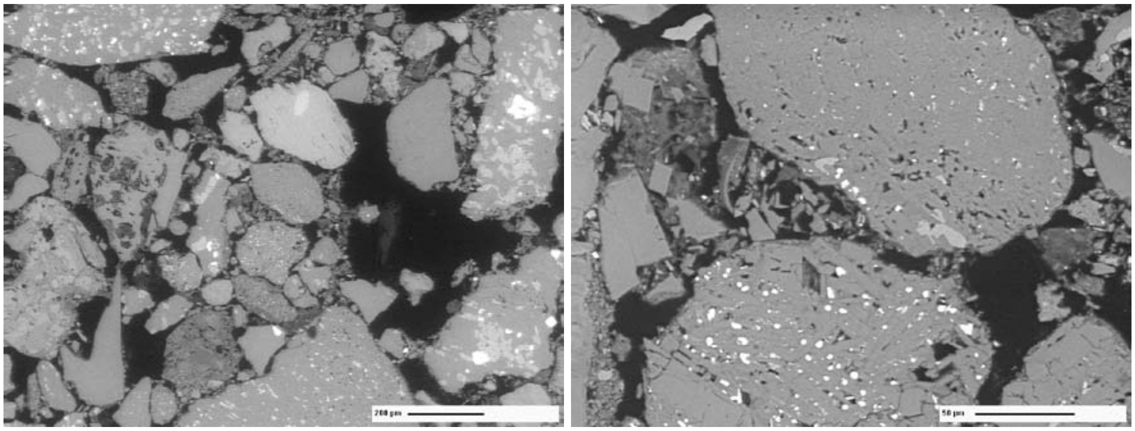

Figure 25. Shevlin Sand and Gravel, 71Z-4, Thin Section P-12,294. The observed grains are chiefly in long contact with few in point contact. Several contact areas and gaps are filled with finer aggregates. Many voids and gaps are filled with fines increasing the surface area of grain contacts. The magnification is 100 and 500X with bar scales of 200 µm (left) and 50 µm (right), respectively.

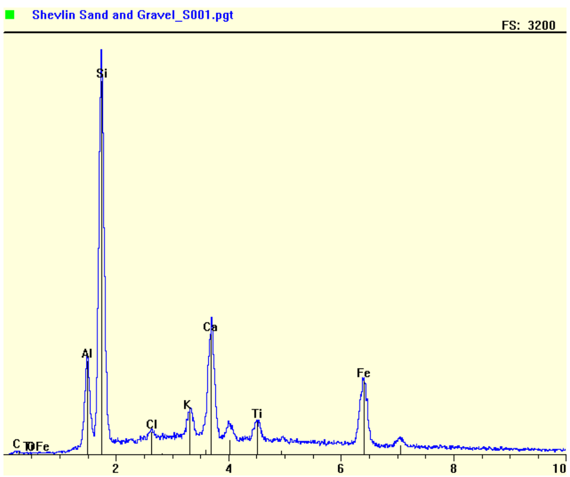

Figure 26. Energy Dispersive X-ray analysis indicates gap filling material in figure 24 (arrow) is likely rock and mineral particles and mineral residue from Denver tap water. The graph shows intensity on the vertical axis and the x-ray energy on the horizontal axis.

Figure 27. CEMEX Limestone Sand (FL), 71Z-8. The images show the irregular surfaces of as-received specimen fragments at two different magnifications. The particles appear subangular and subrounded in shape. The field on the left image is about 16 mm width and the field on the right is 6 mm width and the corresponding magnification are about 6X and 17X, respectively.

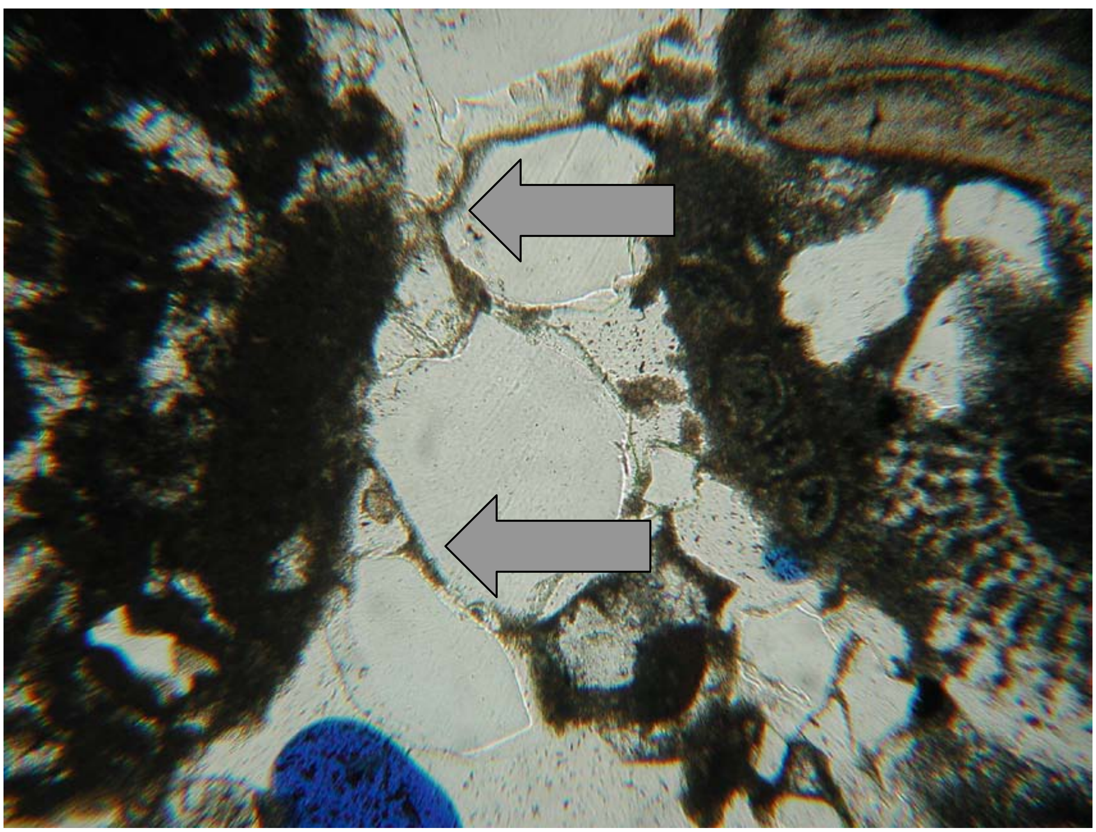

Figure 28. CEMEX Limestone Sand (FL), 71Z-8, Thin Section P-12,295. The image shows typical grain relationships including chiefly long contacts and few point contacts. The specimen appears well packed due to cementation. Calcium carbonate cement obscures many grain contacts (gray arrows). The limestone particles appear subangular and subrounded with a few angular and rounded in shape. The inter-granular contact area is filled with calcium carbonate crystals which act as a binder. The area between grains is void space filled by epoxy material. The field width of the image is about 1.2 mm with a magnification of about 170X.

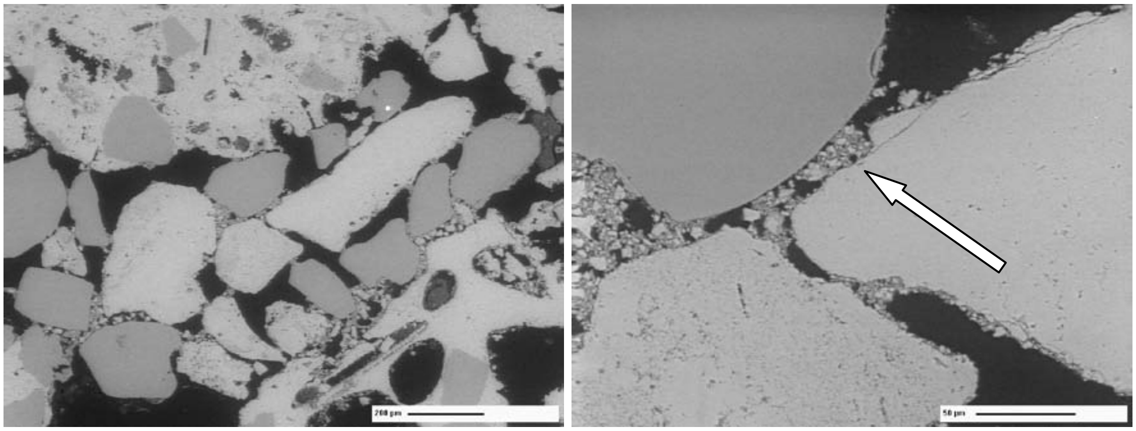

Figure 29. CEMEX Limestone Sand (FL), 71Z-8, Thin Section P-12,295. The grains are in long and point contact with numerous contact areas and gaps filled with calcium carbonate. There is ample evidence of a binder at grain contacts (arrow). The magnification is 100 and 500X with bar scales of 200 μm (left) and 50 μm (right), respectively.

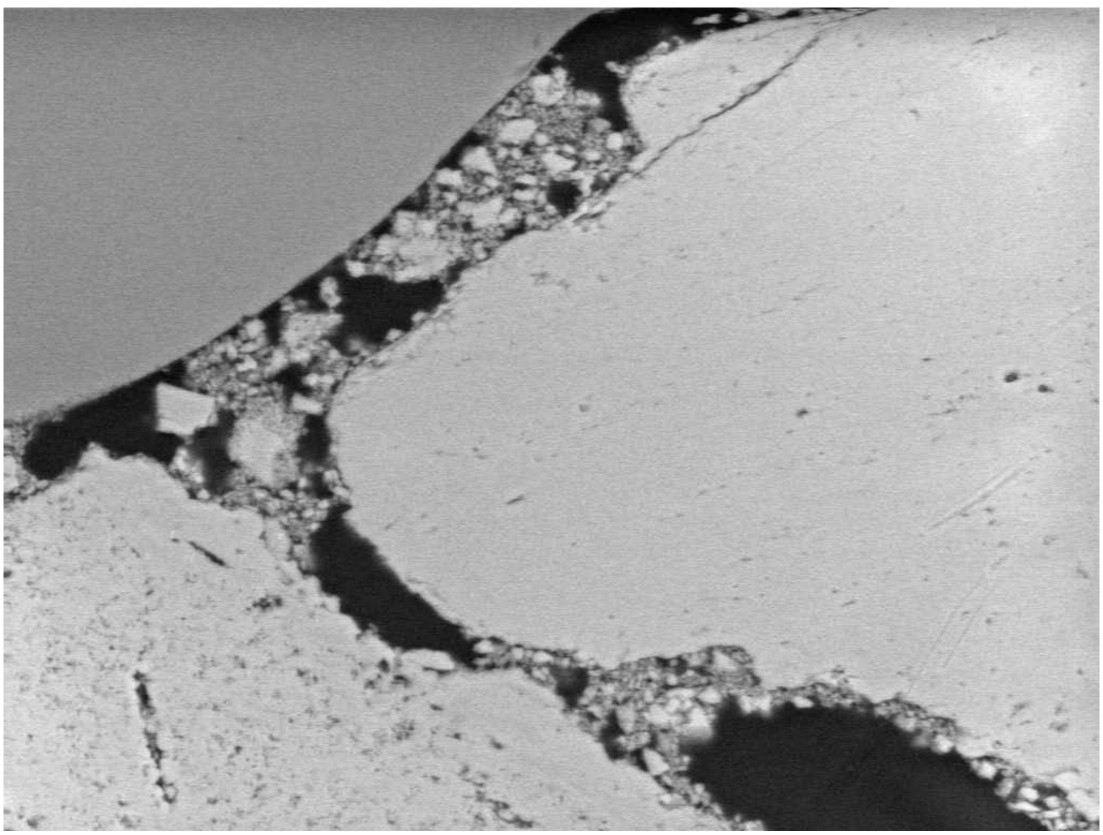

Figure 30. The higher magnification image shows fine particle bonds bridging grain contacts in figure 29. The image was acquired at a magnification of 1000X; a scale marker is not available.

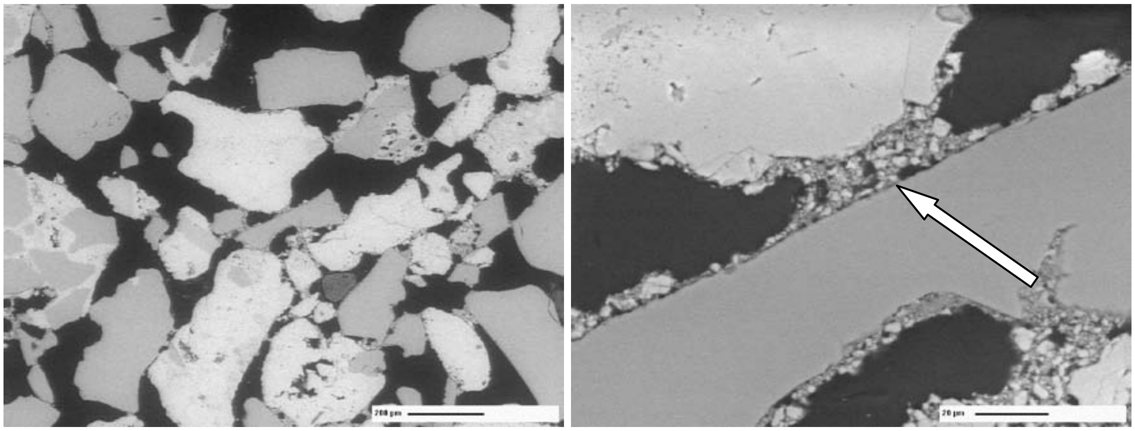

Figure 31. CEMEX Limestone Sand (FL), 71Z-8, Thin Section P-12,295. The grains are in long and point contact with numerous contact areas and gaps filled with calcium carbonate. There is ample evidence of a binder at grain contacts (arrow). The magnification is 100 and 1000X with bar scales of 200 µm (left) and 20 µm (right), respectively.

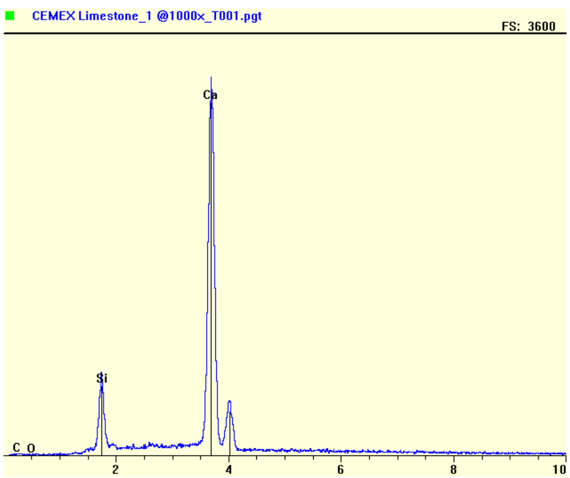

Figure 32. Energy Dispersive X-ray analysis indicates gap filling material in figures 30 and 31 is calcium carbonate. The graph shows intensity on the vertical axis and the x-ray energy on the horizontal axis.

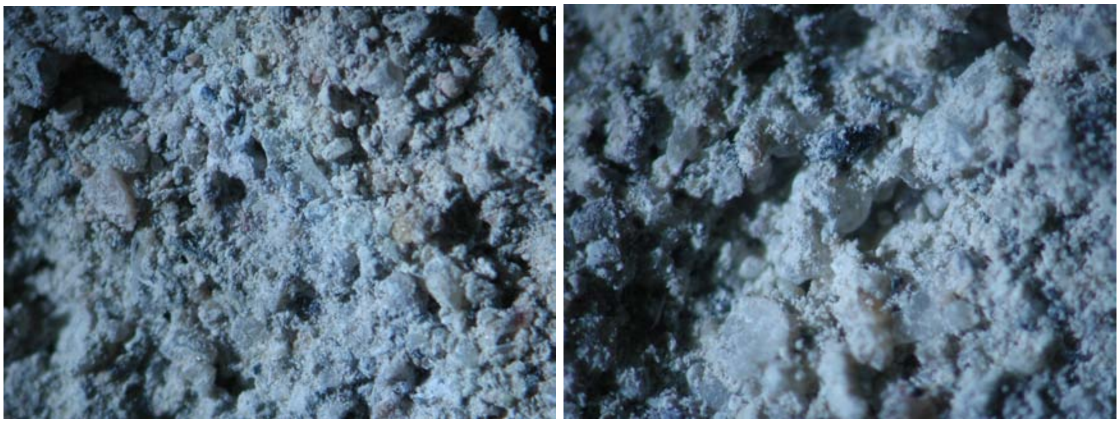

Figure 33. Recycled Concrete, 71Z-1. The images show the irregular surfaces of as-received specimen fragments at two different magnifications. The particles appear subangular and subrounded in shape. The field on the left image is about 16 mm width and the field on the right is 6 mm width and the corresponding magnification are about 6X and 17X, respectively.

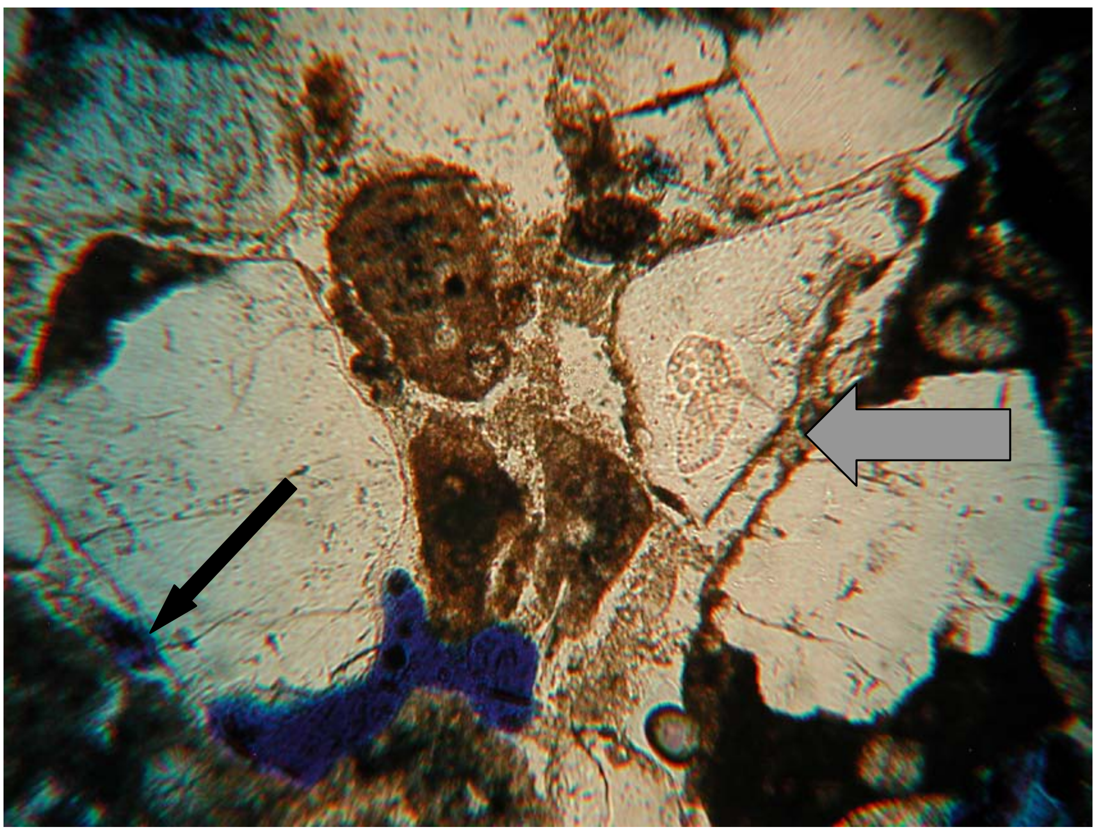

Figure 34. Recycled Concrete, 71Z-1, Thin Section P-12,296. The image shows typical grain relationships including long contacts (black arrow). The Portland cement and aggregate particles appear subangular and subrounded in shape and well packed. The grain contact areas are filled with apparent Portland cement paste which acts as a binder. Calcium hydroxide (Portlandite), which is a component of hydrated Portland cement, has likely leached from the cement paste and reacted with air to carbonate the crushed Portland cement paste fragments which acts as a binder between grains (gray arrow). The area between grains is void space filled by epoxy material and carbonated concrete paste. The field width of the image is about 1.2 mm with a magnification of about 170X.

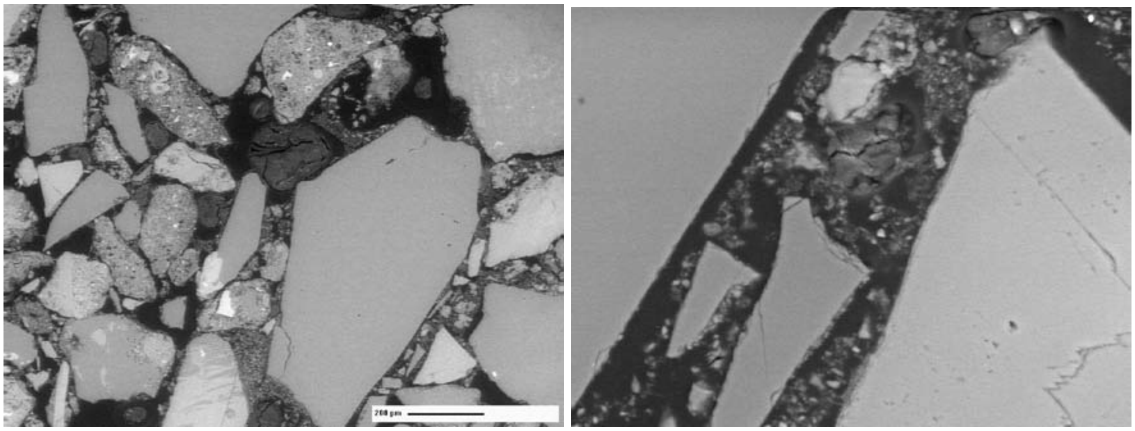

Figure 35. Recycled Concrete, 71Z-1, Thin Section P-12,296. The grains are in long, concavo-convex and point contact with numerous contact areas and gaps filled with apparent carbonated Portland cement paste particles. There is ample evidence of a binder at grain contacts. The magnification is 100 and 1000X with bar scales of 200 μm (left) and 20 μm (right), respectively.

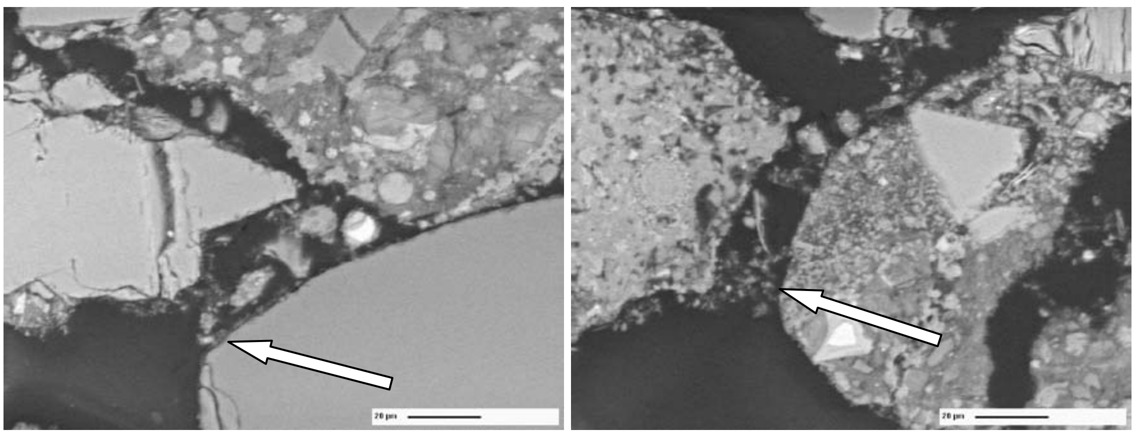

Figure 36. Recycled Concrete, 71Z-1, Thin Section P-12,296. Observed contact areas and gaps filled with apparent carbonated Portland cement paste particles. There is ample evidence of a binder at grain contacts (arrows). The magnification is 1000X with a bar scale of 20 μm in each image.

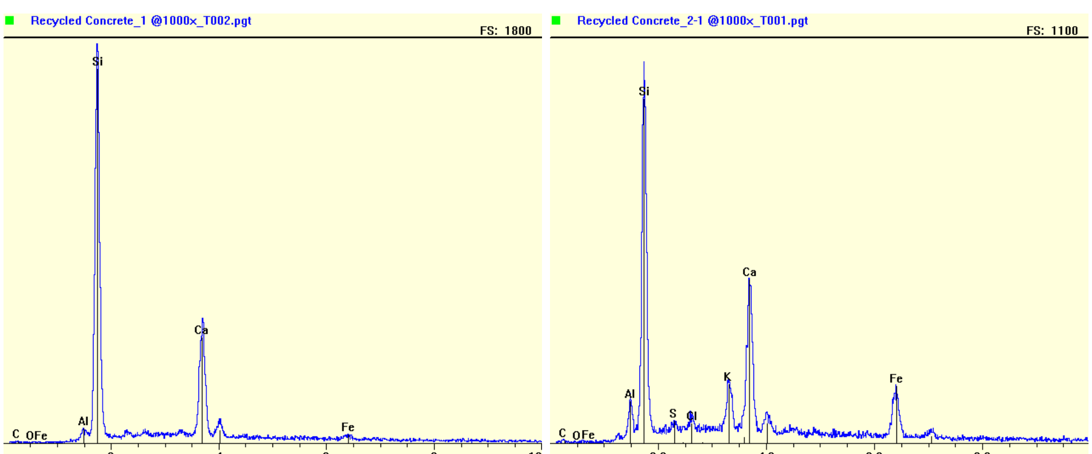

Figure 37. Energy Dispersive X-ray analysis indicates gap filling material in figures 35 and 36 is likely carbonated Portland cement paste and calcium carbonate. The graph shows intensity on the vertical axis and the x-ray energy on the horizontal axis.