Engineering Properties of Foamed Recycled Glass as a Lightweight Fill

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ABSTRACT: This paper presents the engineering properties of a lightweight-foamed glass aggregate (LWA-FG) for consideration as a lightweight fill material for use in retaining structure, embankment, highway, and bridge abutment construction in the United States. A laboratory study was conducted to evaluate the effect of compaction energy on the gradation, compression and direct shear strength of LWA-FG produced in the United States by Aero Aggregates, LLC. Dry and wet particle-size analyses were conducted before and after each of the engineering property tests to determine the amount of particle breakage due to the crushing effect of the impact and vibratory compaction, static compression, and/or direct shear testing. The results indicate the normally uniformly graded LWA-FG (as produced) transforms into an increasingly well graded material as a function of increasing compactive effort, static loading, and shear conditions. Therefore, the engineering properties of unit weight, compressibility, and shear strength of the LWA-FG are directly influenced by the amount of particle breakage and changes in particle distribution during processing. Useful laboratory test data for comparison to field observations and measured field performance are provided from this limited study.

1. INTRODUCTION

In the 1980's foamed glass production was started in Switzerland and Germany using cleaned recycled glass. Lightweight-foamed glass aggregates (LWA-FG) were originally produced in Scandinavia during the 1990's for use as a thermal barrier in road construction. LWA-FG has been successfully used in building and infrastructure construction in Europe for more than 20 years. Current civil engineering challenges include construction on soft soils, reduction in lateral earth pressures, decreased loads on structures and protection of underground utilities. LWA-FG are being positioned to address a lot of these challenges due to their lightweight, high frictional strength, thermal insulation, and free draining properties as a sustainable solution based on the beneficial reuse of glass containers.

Work by Betti et al. (2014) on two types of LWA-FG manufactured by the Misapor A/G company shows there is significant particle breakage of the LWA-FG through the use of gyratory compaction. The materials tested were similar in gradation but had different bulk unit densities ranging from 400 to 460 kg/m^3 (24.9 to 28.7 pcf). There was an increase in dry unit weight with increased compactive effort as well as an increase in California Bearing Ratio (CBR) up to an optimum value between 60 to 120 cycles of gyration. Arulrajah et al. (2015) conducted testing on LWA-FG material which was provided by a supplier in Melbourne, Australia. Their studies focused on evaluating the engineering and environmental properties of the LWA-FG. Their work showed that the LWA-FG had satisfactory engineering and environmental properties which indicated that the material would be ideal for its use as a lightweight fill material. A summary of their key results are presented in Table 1.

This paper will present select engineering properties of LWA-FG for consideration as a lightweight fill material for use in retaining structures, embankments, highway, and bridge abutment construction in the United States. A preliminary laboratory study was conducted to evaluate the effect of compaction energy on the gradation, compression (consolidation), and direct shear strength behavior of LWA-FG. In the study, dry and wet particle-size analyses were conducted before and after several of the engineering property tests to determine the amount of particle breakage due to the crushing effect of the impact and vibratory compaction, static compression, and/or direct shear testing.

TABLE 1. Key results of lightweight fill material (Arulrajah et al. (2015))

Engineering Parameters	*Lightweight Fill Material*
D_{10} (mm)	0.13
D_{30} (mm)	1.2
D_{60} (mm)	20.6
C_u	158
C_c	0.53
Gravel sized particles (4.75 – 40 mm (%))	66
Sand sized particles (0.075 – 4.75 mm (%))	32
Clay/Silt sized particles (< 0.075 mm (%))	2
Minimum dry density (kg/m^3)	170
Maximum dry density (kg/m^3)	290
Peak cohesion by direct shear under normal stresses of 10 to 40 kPa (kPa)	23.4
Peak friction angle by direct shear under normal stresses of 10 to 40 kPa (degrees)	55.7

2. TESTING PROGRAM

2.1Materials

The LWA-FG material that was used in this study was manufactured by Aero Aggregates, LLC (Aero Aggregates), Bensalem, Pennsylvania, one of the first United States (USA) based companies to produce LWA-FG from 100% recycled glass in response to the growing needs and increased requirements for lightweight construction materials. Figure 1 presents a typical example of the LWA-FG after production. Some typical values provided by the manufacturer indicate the particle size ranges from 10 to 60 mm (0.39 to 2.36 in) and has a bulk density of 210 kg/m^3 (13.1 pcf). A typical particle size distribution of the LWA-FG provided by the manufacturer is presented in Figure 2.

FIG. 1. Typical example of the LWA-FG after production.

The manufacturer provided two (2) 0.21-m^3 (55-gal) barrels of the LWA-FG material for evaluation. Upon receipt of the material, the bulk samples were thoroughly mixed and split down into desirable sample sizes. The following ASTM standard practices were used to prepare the LWA-FG for testing ASTM C702/C702M (2011a) and ASTM D75/D75M (2014a). After sample preparation, the initial moisture content was measured following ASTM D2216 (2010), grain size distributions were determined following ASTM C136/136M (2006) and the initial bulk density was measured following ASTM C127 (2012a) on the as-received LWA-FG to compare to the manufacturers data. The average moisture content was determined to be 1.06% and the average bulk density was determined to be 227.2 kg/m^3 (14.2 pcf). Three sieve analyses were performed following the dry sieving method on the LWA-FG and are presented in Figure 2 along with the typical particle size distribution provided by the manufacturer. Figure 2 shows the material that was provided for evaluation has a finer grain size then the typical data provided by the manufacturer with particle size ranging from 10 to 30 mm (0.39 to 1.18 in) but is still a very uniformly graded material. This difference in gradation also supports the increase in the bulk unit weight from 210 kg/m^3 (13.1 pcf) to 227.2 kg/m^3 (14.2 pcf) a change of approximately one (1) pcf.

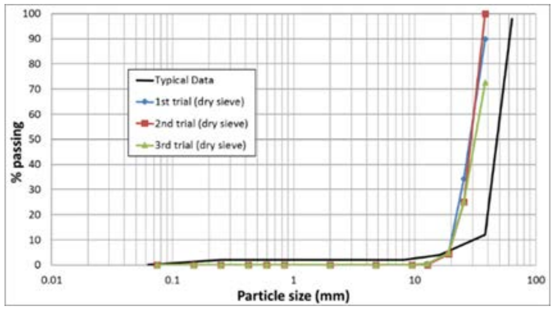


FIG. 2. Particle size distribution of the as-received LWA-FG material compared with the manufacturer's typical data.

2.2Testing Methodology

A testing program was developed to evaluate the change in particle size distribution as a function of the effect of compaction energy (impact and vibratory), compression (sustained static compression and creep) and direct shear behavior. In the study, dry and wet particle-size analyses were conducted after each of the engineering property tests to determine the amount of particle breakage due to the crushing effect of the impact and vibratory compaction, static compression, and/or direct shear testing. Each of these post particle-size analyses were then compared to the average as-received particle-size analysis of the LWA-FG selected as the first (1st) trial dry sieve test shown in Figure 2.

2.2.1Effect of Compaction Energy

To study the effect of compaction energy two impact compaction tests and a vibratory compaction test were conducted on the LWA-FG material. The first impact compaction test was conducted as a single specimen test compacted under dry conditions following ASTM D1557 (2012c) method C. The test was conducted with a 44.48 N (10 lbf) hammer being dropped from a height of 457.2 mm (18 in) 56 times into a 152.4 mm (6.0 in) diameter mold having a height of 116.8 mm (4.6 in) with 5-layers of the LWA-FG material developing a compactive effort of 2,700 kN-m/m^3 (56,000 lbf-ft/ft^3). The second impact compaction test was also conducted as a single specimen test compacted under dry conditions following a modified version of ASTM D1557 (2012c) method C. The test was conducted with a 44.48 N (10 lbf) hammer being dropped from a height of 457.2 mm (18 in) 25 times into a 152.4 mm (6.0 in) diameter mold having a height of 116.8 mm (4.6 in) with 5-layers of the LWA-FG material developing a compactive effort of 1,200 kN-m/m^3 (25,000 lbf-ft/ft^3). The second test used a lower level of compactive effort which was approximately half of the modified energy per ASTM D1557 (2012c) and twice the energy of the standard energy per ASTM D698 (2012b).

In addition to the impact compaction tests, a vibratory compaction test was conducted following ASTM D4253 (2014b) to determine the maximum index density and unit weight of the LWA-FG. The test was conducted on a single test specimen under dry conditions using a 279.4 mm (11 in) diameter mold having a height of 231.8 mm (9.125 in). For comparison a minimum index density and unit weight test was conducted on the LWA-FG following ASTM D4254 (2014c) using the same size mold.

2.2.2Effect of Static Compression

To study effect of static compression on the LWA-FG material two one-dimensional (1-D) sustained static compaction tests were conducted following ASTM D2435/D2435M (2011b). Eight incrementally increasing static loads (loading) were applied by doubling the load increment ranging from 6 kPa to 766 kPa (125 up to 16,000 psf) and three incremental decreasing static loads (unloading) from 766 kPa (16,000 psf) to 12 kPa (250 psf) in increments of 192, 48 and 12 kPa (4,000, 1,000 and 250 psf). The first test was conducted with load durations of 15 minutes and the second test was conducted with load durations of 4 hours.

In addition to the incrementally loaded sustained static compaction test, a sustained load (creep) test was conducted following the methodology of ASTM D2435/D2435M (2011b) on the LWA-FG material. In this test, a constant load of 24 kPa (500 psf) was maintained on the specimen of LWA-FG for 10,025 minutes (approximately 7 days) where vertical deformation measurements were taken every 5 minutes.

2.2.3Effect of Direct Shear Testing

To study the effect of direct shear testing on the LWA-FG material two sets of direct shear tests were conducted following ASTM D3080/D3080M (2011c) using a large scale direct shear device. The shear box was 305 mm by 305mm (12 in by 12 in) in plane and had a total depth of 153 mm (6 in). Each set of tests (a test series) was conducted under a range of normal stresses where each normal stress was applied for 15 minutes prior to the initiating shear deformation at a rate of 1 mm/min (0.04 in/min). The first test series was conducted on the as-received LWA-FG material placed in the shear box with no compactive effort (at approximately the bulk density) under the normal stresses of 14.4, 35.9, 57.5, 144, 287, and 426 kPa (300, 750, 1200, 3,000, 6,000 and 8,900 psf). The second test series was conducted using LWA-FG material that had undergone modified Proctor compaction ASTM D1557 (2012c) method C energy and then placed in the shear box for testing under the normal stresses of 144, 287, and 426 kPa (3,000, 6,000 and 8,900 psf). All of the direct shear tests were conducted under dry conditions.

3. RESULTS AND DISCUSSIONS

3.1Effect of Compaction Energy

The results from the first impact compaction test following ASTM D1557 (2012c) method C produced a density of 612 kg/m^3 (38.23 pcf). During the second test using a modified level of compactive energy produced density of 536 kg/m^3 (33.48 pcf). This is a significant increase in density compared to the average bulk density of the as-received material (227.2 kg/m3 (14.2 pcf)). This is an increase of 2.4 to 2.7 times in density due primarily to amount of particle breakage from the crushing effect of the compactive energy. This particle breakage is shown in Figure 3.

After initial sieving using the dry method a visual observation was made that there seemed to be excess fines attached to the broken particles of the LWA-FG material. Additional sieving was conducted using the wet method, which clearly shows the effect of the fine content that was attached to the larger particles. Figure 3 presents the differences between dry and wet sieving on the LWA-FG material after impact compaction. It can be seen that the uniformly graded as-received LWA-FG material has transformed into a well-graded material because of the impact compaction. This change in particle distribution will have a significant effect on the engineering properties of the LWA-FG material.

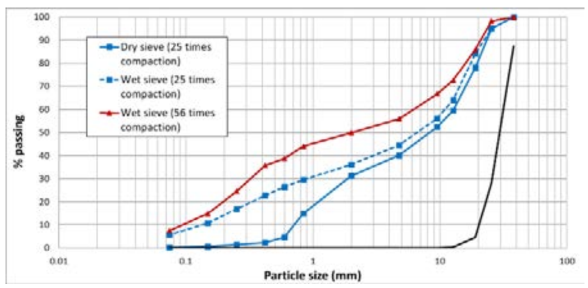


FIG. 3. Particle size distribution of impact compacted specimens of LWA-FG compared to the as-received LWA-FG material.

The results from the vibratory compaction test produced a maximum index density of 325 kg/m^3 (20.29 pcf). This is an increase in density compared to the minimum index density of 227 kg/m^3 (14.18 pcf) which is also very similar to the measured average bulk density. Though this change in density is an increase of 1.4 times it is primarily due to the rearrangement of the particles and not due to a significant change in particle distribution as shown in Figure 4. Because there was very little particle breakage, only the dry method of sieving was used. Additionally, the particle distribution remained uniformly graded when compared to the as-received material with the particles becoming slightly finer in distribution.

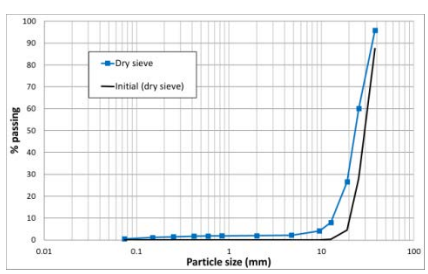


FIG. 4. Particle size distribution of vibratory compacted specimen of LWA-FG material compared to the as-received LWA-FG material.

3.2Effect of Static Compression

The results from the static compression testing on the LWA-FG following ASTM D2435/D2435M (2011b) are presented in Figure 5. There was very similar stress – strain behavior for both loading durations through a vertical stress of 96 kPa (2,000 psf). Once the vertical stress increment increased beyond 192 kPa (4000 psf) there was an increase in vertical strain for the longer load duration of 4 hours. Additionally, since the LWA-FG material is a granular material there was no significant rebound response due to the unloading back to a vertical stress of 12 kPa (250 psf).

Looking at the vertical displacement vs. log of time plots yielded an unreliably determination of the coefficient of consolidation since the behavior of the LWA-FG does not following the traditional theory of 1-D consolidation since the material is granular in nature. To address this an analysis of the secondary slope of the vertical displacement vs. log of time plots was made. This was accomplished by determining the slope of the displacement – time curve for the 15-minute load duration tests between 4 and 15 minutes and the corresponding vertical deformations for each test. For the 4-hour load duration tests, the slope was determined between 1 and 4 hours for and the corresponding vertical deformations each test. Figure 6 presents the calculated slopes, which have been identified as secondary slopes vs. vertical stress. Looking at the results in Figure 6 clearly shows that the 15-minute load durations had a higher secondary slope for all of the loading increments compared to the 4-hour load durations which indicates that vertical displacement (settlement) was still continuing at the time the tests were terminated.

Figure 7 presents the change in particle size distribution of the LWA-FG material due to the static compression (1-D consolidation) testing. Since the 4-hour load duration tests produced a larger amount of vertical strain compared to the 15-minute load duration tests this data has been presented for both wet and dry sieve methods. The particle distribution curves show that the LWA-FG material has become more well graded then uniformly graded when compared to the as-received material with the particles becoming increasing finer in distribution. Additionally, there is very little difference between the wet and dry sieve results.

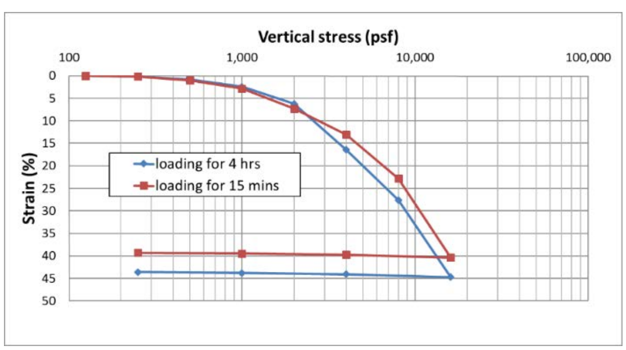


FIG. 5. Vertical stress vs. strain behavior of the LWA-FG material under load durations of 15 minutes and 4 hours.

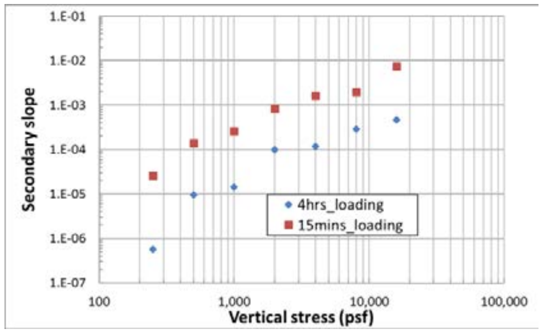


FIG. 6. Secondary slope vs. vertical stress behavior of the LWA-FG material.

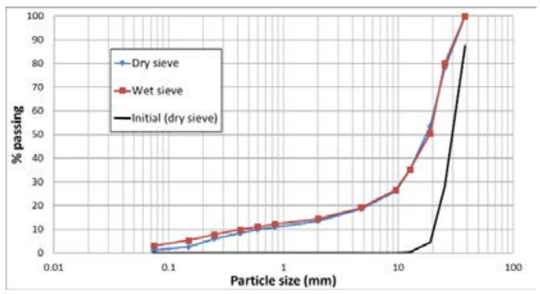


FIG. 7. Particle size distribution of static compression specimen of LWA-FG.

The results from the sustained load (creep) test conducted following the methodology of ASTM D2435/D2435M (2011b) on the LWA-FG material are presented in Figure 8. In this test, a constant load of 24 kPa (500 psf) was maintained on the specimen of LWA-FG for 10,025 minutes (approximately 7 days). Looking at tail of the vertical strain vs. time plot (Figure 8) starting at 6000 minutes and continuing to the end of the test shows a decreasing slope, which indicates a creep strain rate of 6.56 x 10^{-6} %/min for the LWA-FG material. Figure 9 presents the change in particle size distribution of the LWA-FG material due to the sustained load (creep) test. Looking at the particle distribution shows very little particle breakage so only the dry method of sieving was evaluated. Additionally, the particle distribution remained uniformly graded when compared to the as-received material with the particles becoming slightly finer in distribution.

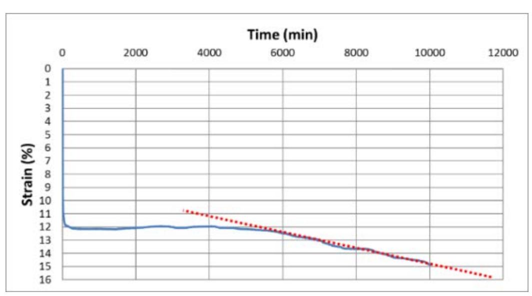


FIG. 8. Vertical strain vs. time for the sustained load (creep) test conducted under a constant vertical stress of 24 kPa (500 psf).

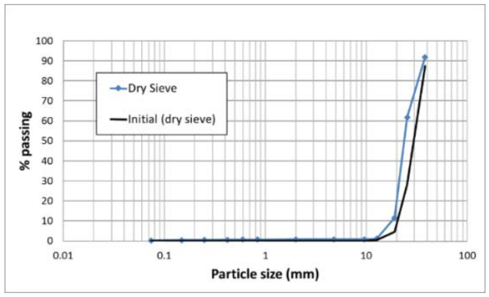
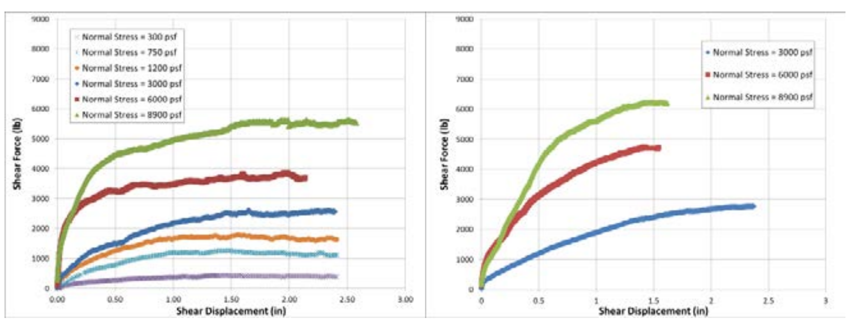


FIG. 9. Particle size distribution of sustained load (creep) specimen of LWA-FG.

3.3Effect of Direct Shear Testing

The results of the direct shear testing conducted following ASTM D3080/D3080M (2011c) using a large-scale direct shear device are presented Figure 10. Figure 10 presents the shear force vs. shear displacements plots for the two sets of direct shear tests. Figure 10a presents the data for the direct shear tests conducted on the as-received LWA-FG material and shows that the material needed to achieve a shear displacement of at least 51 mm (2 in.) to reach a maximum shear strength with very little to no shear strength reduction once the peak shear strength was reached. Figure 10b presents the data for the direct shear tests conducted on the modified LWA-FG material and shows that the material needed to achieve a shear displacement of at least 38 mm (1.5 in.) to reach a maximum shear strength again with very little to no shear strength reduction once the peak shear strength is reached. The test conducted under a normal stress of 144 kPa (3000 psf) on the modified LWA-FG material performed similar to the as-received LWA-FG material requiring a larger amount of shear displacement to achieve the maximum shear strength.



a) b)

FIG. 10. Shear force vs. displacements plots from direct shear testing, a) as-received LWA-FG and b) modified LWA-FG.

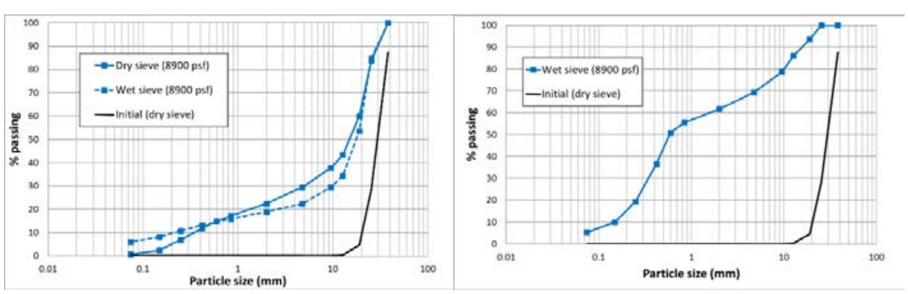
The fitted shear strength parameters for the testing performed on LWA-FG material are presented in Table 2. Looking at the fitted shear strength parameters for the as-received LWA-FG material there is clearly a curvilinear response in the development of shear strength as a function of normal stress. The shear strength parameters for the low normal stress range (14.4 to 57.5 kPa) are very similar to those that are presented in Table 1. Additionally, there is a transition point around the normal stress of 96 kPa

(2000 psf) where the shearing behavior of the particles switches from a frictional response (high friction angle) to a crushing response (lower friction angle and an increase in cohesion). This point of transition around 96 kPa (2000 psf) can also be seen in Figure 6 where there was significant increase in vertical deformation. Based on the measured shear strength parameters for the high normal stress range (144 to 426 kPa) there is an increase in frictional strength as a function of modified particles due to the modified compactive energy prior to shear displacement. If this material were a naturally formed gravel material having a similar particle distribution, one would anticipate cohesion closer to zero for the applied range of normal stresses. The measured cohesion indicates a strength that develops independent of normal stress that is a function of additional particle degradation due to the shearing of the particles.

TABLE 2. Measured shear strength parameters of LWA-FG

Tested Material	Range of Normal Stress (kPa)	Peak Friction Angle (°)	Peak Cohesion (kPa)
As-received LWA-FG	14.4 to 57.5	56	2.1
As-received LWA-FG	35.9 to 144	29	45.8
As-received LWA-FG	144 to 426	27	46.0
Modified LWA-FG	144 to 426	31	51.5

Figure 11 presents the change in particle size distribution of the LWA-FG material due to direct shear testing. Figure 11a presents the particle distribution curves for the as-received LWA-FG material after testing for both wet and dry sieve methods. Figure 11b presents the particle distribution curve for the modified LWA-FG material after testing for only the wet sieve method. From Figure 11a there was clearly an effect of wet sieving compared to the dry sieve method since the amount of particle degradation was similar to what was found during the impact compaction tests on the LWA-FG material. Similar to the impact compaction tests it can be seen that the uniformly graded as-received LWA-FG material has transformed into a well-graded material because of the direct shear testing and the modified LWA-FG material has become increasingly more well graded. Again, this change in particle distribution has a significant effect on the engineering properties of the LWA-FG material especially with regard to the direct shear strength of the material.



a) b)

FIG. 11. Particle size distribution of LWA-FG after direct shear testing, a) as-received LWA-FG and b) modified LWA-FG with comparison.

4. CONCLUSIONS

A preliminary laboratory study has been presented to evaluate the effect of compaction energy on the gradation, compression (consolidation), and direct shear strength behavior of a LWA-FG material produced in the USA. This paper has provided useful laboratory testing data showing the effect of particle breakage on the engineering property testing of LWA-FG material for comparison to field observations and measured field performance, which should be the focus of continuing study. Figure 13 presents a summary of the particle size distributions for the various engineering property tests on the LWA-FG material with a comparison to the as-received LWA-FG material.

From the data presented in Figure 12, the LWA-FG material is a very brittle material that improves its mechanical engineering properties as a function of particle breakage. The material transforms from a uniformly graded material to a very well graded material as a function of compaction energy through either impact or direct shear testing. Static loading when the vertical stress is greater than 192 kPa (4,000 psf) has a moderate effect on the particle distribution and producing finer particles approaching a well graded distribution. The effect of vibratory compaction has very little effect on the particle distribution allowing the LWA-FG to maintaining a uniform gradation with slightly finer particles.

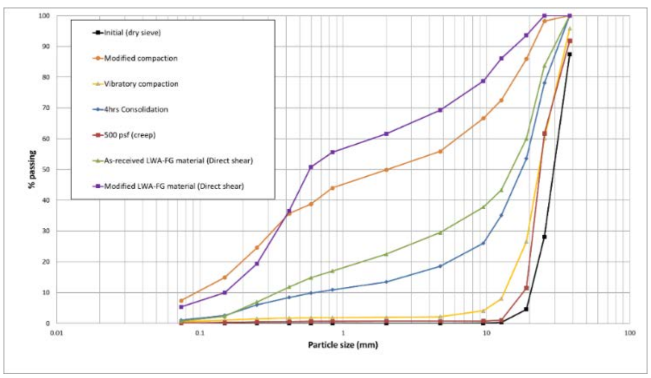


FIG. 12. Summary of particle size distributions for the various engineering property tests on the LWA-FG compared to the as-received LWA-FG.

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