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Particle Size Effects on Breakage of ACT Aggregates Under Physical and Environmental Loadings

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Abstract

Aggregates manufactured from fine-grained thermal waste residues using accelerated carbonation technology (ACT) represent a potential sustainable alternative to natural aggregates. However, for these manufactured products to compete with virgin stone in geotechnical applications, their durability under mechanical and environmental loadings must be assessed. This paper describes particle breakage that occurs for different grain sizes (entire sample, 5mm-2.5mm, and 2.5mm-1.25 mm) of a cement kiln dust accelerated carbonated manufactured aggregate after undergoing triaxial compression, triaxial shear and freeze/thaw (f/t) testing. It is shown that the particle breakage of the aggregate is dominated by the larger (5mm-2.5mm) size fraction of the sample under all loading conditions. Particle breakage results from f/t testing showed that the 5mm-2.5mm size corresponded to similar or slightly less particle breakage than that under triaxial shear, while the particle breakage of the 2.5mm-1.25mm aggregate after 20 cycles of freeze-thaw was relatively small. The performance of the carbonated aggregate in terms of relative breakage was similar or slightly better than natural calcareous sand results in the literature.

Keywords: manufactured aggregate, particle breakage, accelerated carbonation, compression, shear, freeze/thaw

Introduction

Sustainable aggregate manufacturing represents a potential solution to limited aggregate supply in some geographical regions, and a sustainable waste management solution for selected high-volume wastes currently landfilled. Challenging regulatory approvals required for environmental permitting in developed countries also suggests that manufactured aggregates will become increasingly important in the future. The use of accelerated carbonation technology (ACT) has been shown to manufacture light-weight aggregates from fine-grained thermal waste residuals while at the same time sequestering CO_2 during the aggregate production process (Gunning et al. 2009). This sustainability aspect of the aggregate has led to the development of ACT manufacturing plants in the United Kingdom. Various researchers (e.g. Fernández et al. 2004; Domingo et al. 2006; Costa et al. 2007) have described the science behind the ACT process and it hence will not be repeated here.

Current application of ACT manufactured aggregates in the United Kingdom is replacement aggregates for concrete blocks (Gunning et al. 2011). For these aggregates to be used in broader applications such as engineered fill for roadway construction, their sustained durability under mechanical and environmental loadings is critical. The durability of coarse-grained soil particles in geotechnical applications has been the subject of numerous studies in the literature due to concerns related to particle breakage (i.e. large dams (Marsal 1967), deep foundations (Klotz & Coop 2001), roadways (Zheghal 2009) and petroleum applications (Zheng & Tannant 2016). Work by Marsal (1967); Lee & Farhoomand (1967); Hardin (1985) represent examples of early studies performed to investigate the durability of soil particles by examining particle breakage. It has been shown in these, and other studies, that the amount of soil particle breakage will depend, inter alia, on the individual soil particle's mineralogy, shape, and size (Lee & Farhoomand 1967; Hardin 1985). Stress level, stress path, and time effects (Coop 1990; Lade et al. 1996; Yamamuro & Lade 1993 Altuhafi & Coop 2011) also play key roles in particle breakage.

Reported ACT manufactured aggregate individual particle strengths are in the order of 0.5 MPa to 1 MPa (Lake et al. 2016) and hence are potentially susceptible to particle breakage, similar to weaker grain soil particles such as calcareous sands (e.g. Coop 1990). As accelerated carbonated aggregates are commercially available and being further developed, data on aggregate breakage under different loadings is needed to elucidate potential applications outside of bound systems. Thus, the purpose of this paper is to provide a relative comparison of particle breakage for an accelerated carbonated aggregate developed from cement kiln dust previously described by Lake et al. (2016). In this paper the manufactured aggregate is subjected to a series of triaxial tests (drained isotropic compression and drained isotropic compression followed by drained axial shear) as well as (f/t) tests. The influence of aggregate size/gradation on the particle breakage is evaluated by examining changes in grain size distributions of the samples by calculating relative breakage, as defined by Hardin (1985). Given that the ACT manufacturing process can control the final size of the aggregate, understanding the role of size in particle breakage is useful as a potential tool for improving the durability performance of the product.

Materials and Methods

Cement Kiln Dust ACT Aggregate Production Process

The testing performed in this paper used a cement kiln dust (CKD) material previously described by Lake et al. (2016). In summary, the material was obtained from a Lafarge cement plant in Brookfield (Nova Scotia, Canada) in August 2014. The CKD consists of calcium, iron, silica, aluminum, magnesium and potassium oxides, with 42% CaO content being the key carbonate-able mineral in producing the aggregate.

The pelleting process for carbonated aggregate manufacturing described by Lake et al. (2016) was modified slightly in an attempt to produce a stronger aggregate than the ~ 1MPa strength from that work. Pelletizing involved pre-mixing 400g (dry mass) of CKD with 130g of water using a laboratory paddle mixer. During this phase of the mixing process, CKD with water was mixed for 45 to 60 seconds at a 50 rpm mixing speed followed by 30 to 60 seconds at 120 rpm. Subsequently, an additional 60g of CKD was added at a 120 rpm mixing speed and then 40g CKD was added to mixer; then mixed for 30 seconds at 50 rpm to produce rounded aggregates. The mix was then placed in a rotating drum with CO_2 saturation for 15 minutes at 50 rpm to complete the process. The carbonated aggregates in this study were air-cured at 20 ± 2°C and ~25% relative humidity conditions in a lab for at least 28 days prior to being subjected to any testing. As reported by Lake et al. (2016), the relative density (i.e. specific gravity) of the aggregates for this process is 2.1. When placed in a loose compaction state, the bulk density is 1200 kg/m^3.

In this paper, three different particle size distributions were assessed for particle breakage. The entire particle size distribution produced from the ACT process, referred to as "EPS" in this paper, was used initially for testing. Additional aggregate was prepared using the same techniques for the EPS but after curing, the aggregate was segregated into two distinct size fractions. This was accomplished by passing the material through the 5 mm sieve, followed by the 2.5 mm sieve, followed by the 1.25

mm sieve. Material retained on the 5 mm sieve and passing the 1.25 mm sieve was discarded. Material retained on the 2.5 mm sieve is referred to as the "5-2.5PS" sample in this paper and the material retained on the 1.25 mm sieve is referred to as the "2.5-1.25PS" sample.

Aggregate Testing

Single Aggregate Pellet Strength

To provide an initial assessment of individual particle strength, a single pellet compressive strength test (ASTM D4179-11, 2011), as described by Lake et al. (2016) was used. Ten (10) samples were taken from the two carbonated aggregate grain sizes prepared (i.e. 5-2.5PS; 2.5-1.25PS) and subjected to single pellet compressive strength tests. The mean value of the strength was reported. Particle strengths were measured at 7, 15 and 27 days of air-curing to allow comparison to aggregates presented by Lake et al. (2016).

Drained Isotropic Triaxial Compression Tests

To assess the extent of particle breakage of the accelerated carbonated aggregate during drained isotropic triaxial compression testing, the three grain sizes were subjected to isotropic compression tests similar to that described by Lake et al. (2016). For the EPS material, two subsamples were taken of the prepared aggregate for each test; one was submitted to a grain size analysis and the second used in the triaxial compression tests. For the compression tests, the given aggregate size was lightly compacted in a split mould (70mm inside diameter x 150mm high) and subjected to saturation under 35 kPa effective confining pressure in a triaxial cell. The sample was then subjected to consolidation under the desired effective confining pressure (600, 800, 1000, 1200 or 1400 kPa) to produce the isotropic compression conditions desired. The 1400 kPa represents the limit of the cell pressure available. The test progressed until the specimen reached equilibrium in a drained state at the desired effective consolidation stress. After this was achieved, the grain size curve (by dry weight) of the sample was determined in order to assess the extent of particle breakage that occurred. For the 5-2.5PS and 2.5-1.25PS material, only the grain size distributions after the compression tests were performed. For all tests, the grain size distributions of samples before and after triaxial testing were plotted and compared visually as well as calculating the relative breakage of the particle using the method developed by Hardin (1985). Hardin (1985) assumed that the breakage of particles terminated when the gradation curve of a soil reached a stable condition (i.e. when the final condition achieved was when all particles were smaller than 0.074 mm (sieve No. 200)). The relative breakage (B_r) of soil can then be calculated from the following equation (Hardin, 1985):

$$B_r = \frac{B_t}{B_p} \quad (1)$$

Where B_p is the breakage potential (calculated as the area between the original grain size distribution curve and a vertical line drawn at the 0.074mm sieve size) and B_t is the total breakage (calculated as the area between the initial and final grain size distribution curves). A value of B_r of zero would mean there was no change in grain size distribution (i.e. no breakage) during testing while a value of one would mean that all particles (i.e. maximum breakage) were reduced to sizes less than 0.074 mm size during testing. Readers can access good visual descriptions of the value Br from Hardin (1985).

Drained Isotropic Compression, Drained Axial Shear Triaxial Tests

To assess the extent of particle breakage of the carbonated aggregate under shearing conditions, the three different particle size fractions (i.e. EPS, 5-2.5PS, 2.5-1.25PS) were subjected to drained isotropic compression followed by drained axial shear. Samples were prepared similarly to those described in the previous section. In summary, the given aggregate size was lightly compacted in a split-mold and subjected to saturation under an effective confining pressure of 35 kPa (ASTM 4767-11, 2011). The sample was then subjected to consolidation under the desired effective confining pressure (600, 800, 1000, 1200 or 1400 kPa) and then subsequently sheared under drained conditions at an axial displacement rate of 1.5 mm/min. Axial loading was terminated at 15% axial strain to provide a common strain level. Similar to the triaxial compression tests described in the previous section, grain size distributions were compared before and after testing and the relative breakage calculated.

Freeze/Thaw Durability Testing

F/t durability testing, similar to that described by Lake et al. (2016) was performed on the three different carbonated aggregate sizes (i.e. EPS, 5-2.5PS, 2.5-1.25PS). To summarize, the aggregate samples were soaked in water for 4 hours and then surface dried for approximately 15min. The test aggregate samples were then subjected to 10 or 20 f/t cycles that included freezing to −17·5 ± 2·5°C for 24h and then thawing in a water bath at room temperature (~20 ± 2°C) for 4h (BSI BS EN 13055-4, 2016). The 20 cycles is recommended in the standard referenced above while 10 cycles allowed an examination of breakage at an intermediate step in the f/t process. At the end of the f/t cycles, the samples were subjected to grain size analyses to compare particle size distributions before and after the f/t cycling. For comparison to triaxial compression and/or triaxial shear testing, relative breakage was calculated at the end of each test.

Results

Single Aggregate Pellet Strength

Particle strengths for the two sizes increased as the curing time increased. The 5-2.5PS aggregate achieved strengths of 1.8 MPa, 2.6 MPa, and 2.9 MPa after 7, 15, and 27 days of curing, respectively. The 2.5-1.25PS aggregate achieved strengths of 2.0 MPa, 2.8 MPa and 3.0 MPa after 7, 15, and 27 days of curing respectively. For these simple particle strength tests, there appears to be little, if any, difference in particle strength between the two particle sizes tested. These test results confirmed that the majority of the aggregate curing was completed after 28 days.

Drained Isotropic Triaxial Compression Testing

<u>EPS</u>

Figure 1 shows the particle size distributions for the EPS size of accelerated carbonated aggregate before and after the drained isotropic triaxial compression tests for the five effective confining pressures employed (600, 800, 1000, 1200, and 1400 kPa). As seen from Figure 1, the grain size distributions of the sample visually changed little during these tests. At the higher confining pressures (1200 kPa and 1400 kPa), the grain size did change slightly as is evident by the increase in the finer fraction of the soil. The resulting relative breakage (B_r) values for the EPS size of ACT aggregate is shown on the inset of Figure 1. Similar to the visual observations noted above, B_r increased as the confining pressure increased; the greatest increase occurring from 1000 to 1200 kPa.

5-2.5PS

Figure 2 shows the particle size distributions for the ACT aggregate before and after the drained isotropic triaxial compression testing for the 5-2.5PS material. The initial particle size distribution is a straight line as there is only one particle size present in this sample. As seen from Figure 2, the grain size distributions of the sample visually changed more than that for the EPS during these tests. It appears when examining these grain size plots that there is a more pronounced effect on particle crushing compared to that of the entire grain size distribution and that as the confining pressure increased, the breakage also appeared to increase (i.e. appearance of more finer grain fraction in the sample). The resulting relative breakage for this size is shown on the inset of Figure 2, and confirms this observation. It is also noted that the relative breakage found for this aggregate size was higher than that of the EPS. This observation of how larger particle size, and grain size uniformity can result in increases in particle breakage is consistent with Cassini et al. (2013) and Altuhafi & Coop (2011).

2.5-1.25PS

Figure 3 shows the particle size distributions for the accelerated carbonated aggregate before and after the drained isotropic triaxial compression testing for the 2.5-1.25PS material. As with the 5-2.5PS material, the initial particle size distribution is a straight line as only one particle size is present in this sample. As seen from Figure 3, the grain size distributions of the sample visually changed less than the 5-2.5PS sample and that of the EPS during these tests. It also appears that there was some minor particle breakage as the confining pressure increased. The resulting relative breakage for this size as shown on the inset of Figure 3 confirms this observation. It is also noted that the breakage parameters found for this size aggregate were lower than that of the EPS and the 5mm-2.5mm sample. This is perhaps not surprising when comparing to the EPS as it is likely most of the particle breakage occurred in the 5mm-2.5mm fraction of the sample.

Drained Isotropic Compression, Drained Axial Shear Triaxial Test

EPS

Figure 4 shows the particle size distributions for the carbonated aggregate before and after the drained triaxial shear testing for the EPS particle size distribution for the five effective confining pressures employed (600, 800, 1000, 1200, and 1400 kPa). As seen from Figure 4, compared to the isotropic triaxial compression tests for the EPS, there was noticeably more particle breakage from the shear testing. There was also more particle breakage as the confining pressure was increased. The resulting relative breakages for the carbonated aggregates are shown on the inset of Figure 4. Similar to the visual observations noted above, the relative breakage increased as the confining pressure increased. Also to note is the higher values of B_r relative to the isotropic triaxial compression tests reported in Figure 1. As will be discussed later, this is due to the higher mean stress in the samples relative to isotropic triaxial compression tests and the shear being generated in the samples.

5-2.5PS

Figure 5 shows the particle size distributions for the carbonated aggregate before and after the drained triaxial shear testing for the 5-2.5PS material. As seen from Figure 5, the grain size distributions of the sample visually changed more than that for the EPS during these tests, similar to that observed for the isotropic triaxial compression tests. It also appears when examining these grain size plots that there is a more pronounced effect on particle crushing compared to that of the EPS and, that as the confining pressure increased, there was the appearance of more of a finer grain fraction. The resulting relative breakage for the carbonated aggregate, as shown on the inset of Figure 5, confirms this observation. It is also noted that the B_r values found for this size aggregate were higher than that of the EPS and that the values of B_r were higher than that for the isotropic triaxial compression tests.

<u>2.5-1.25PS</u>

Figure 6 shows the particle size distributions for the 2.5-1.25PS carbonated aggregate before and after the drained triaxial shear testing. As seen from Figure 6, the grain size distributions of the samples for triaxial shear visually changed less than both the 5-2.5PS sample and that of the EPS during these tests. It does visually appear that there was some minor particle breakage as the confining pressure increased, albeit less than the other two sizes. The resulting relative breakage (B_r) for the 2.5-1.25PS material, as shown on the inset of Figure 6, confirms this observation. It is also noted that the particle breakage found for this size aggregate was lower than that of the EPS and the 5mm-2.5mm sample. Also noted is the relative increase in B_r compared to triaxial compression testing.

Freeze/Thaw Cycle Effect on Particle Breakage

Figure 7 shows the grain size distribution of the EPS before and after f/t cycle testing. After 10 cycles of f/t it is apparent that the grain size distribution of the EPS has a finer grain size distribution and after 20 cycles of f/t, this particle size became even finer. The percent passing the 2.5 mm sieve has increased the most in both instances, indicating the larger portion of the sample may be exhibiting more breakage. This phenomenon of particle breakage of the larger size aggregate can be examined further when examining the isolated sizes. The 5-2.5PS material exhibited significantly more breakage than that of 2.5-1.25PS. The 2.5-1.25PS grain size curve visually changed little.

Although particle breakage is usually for mechanical loading applications, it is interesting to calculate B_r for the f/t cycle tests (see inset of Figure 7). The values of B_r corresponded with the visual observations of the grain size curves (more breakage with f/t cycles at 20 than 10; at a given f/t/ cycle, breakage increases 5-2.5PS>EPS>2.5-1.25PS).

Discussion

Particle Breakage Comparison between Triaxial Compression, Triaxial Shear, and Freeze/Thaw Testing

It is useful to compare the particle breakage obtained from the triaxial compression, triaxial shear, and f/t cycle testing to ascertain the effect that different loading conditions would have on the particle breakage of the carbonated aggregate. Figure 8 shows the values of B_r obtained from these three different test methods. For ease of comparison, results are presented in terms of mean stress, ρ' ($\rho' = (\sigma'_1+\sigma'_2+\sigma'_3)/3$) where σ'_1 and σ'_3

($\sigma'_2 = \sigma'_3$ for these triaxial tests) are the major principal effective stress (i.e. axial stress) and minor principal stress (i.e. effective confining stress) at failure. Since triaxial compression and triaxial shear tests were performed under the same effective confining pressures, the use of mean stress, ρ', allows the "additional" axial stress to be accounted for when examining stresses. For the purpose of this paper, the mean stress at the end of the 15% strain level (i.e. termination of the test) was used. It should also be noted that the f/t tests were performed under "zero external mean stress" conditions and hence the grey shading observed on Figure 8 represents the range of B_r values for the 10 and 20 f/t cycles for each particle size.

As previously discussed, it is apparent that for the various triaxial tests, the influence of shear resulted in the highest amount of particle breakage (i.e. when comparing similar mean stresses). As discussed by Coop (1990), the true measure of particle breakage is obtained from critical state conditions (which were not reached in these tests) and hence this must be remembered when examining these test results.

It is noted that for a given loading condition, the 5-2.5PS aggregate underwent more relative breakage (B_r) than that of the 2.5-1.25PS aggregate. When one examines the f/t cycle testing results relative to the triaxial compression and triaxial shear results, it is interesting to see that the particle breakage from f/t cycle testing for the EPS and 5mm-2.5mm size corresponds to much higher particle breakage than triaxial compression (for similar particle sizes) testing but similar to slightly lower particle breakage as that under triaxial shear. This suggests that environmental factors such as f/t cycle may be just as important a design consideration for the ACT aggregate as that compared to loading conditions. In contrast, the particle breakage of the 2.5-1.25PS aggregate after 20 cycles of f/t is relatively small and similar in magnitude to the same size aggregate under triaxial compression test conditions.

Comparison of ACT Aggregate Particle Breakage to Other Studies

Even though there are many different approaches to assessing particle breakage in the literature, it is useful to try, at least from a qualitative standpoint, to compare particle breakage obtained from this study to that of previous studies. For the purposes of this study, calcareous sands studied by Shipton & Coop (2012) (using data from Coop (1990)) and Shahnazari & Rezvani (2013) as well as predominantly silica sands tested by Mun & McCartney (2017) are used as reference materials. The silica sand tested by Mun & McCartney (2017) is relatively durable compared to the calcareous sands tested by Coop and his coworkers. These two types of materials represent natural aggregates, both used in construction applications.

For this research, some values for B_r for other studies were estimated visually from plots and hence this may lead to some discrepancy. However, from a qualitative perspective, approximations were deemed sufficient. Also to note is that the results of Shipton & Coop (2012) and some of Shahnazari & Rezvani (2013) were a mix of isotropic compression tests and drained triaxial shear tests. As well, the tests by Shipton & Coop (2012) were run to higher strain levels than this study (i.e. would account for more particle breakage).

Figure 9 shows B_r values for the various studies. Also shown on Figure 9 are the results for the 5-2.5PS aggregate and the 2.5-1.25PS aggregate in this study. The results of the EPS in this study always fell between these two samples and hence are not included on Figure 9 for clarity purposes. As shown on Figure 9, at a given B_r, it took significantly more mean stress for Mun and McCartney (2017) to achieve the same particle breakage as compared to the ACT aggregate in this study. This is not surprising given the relative differences in mineralogy and individual particle strengths of the aggregates. If one compares the ACT manufactured aggregate to the natural calcareous sand results for similar values of B_r it can be seen that similar or less mean stress is required to achieve a similar particle breakage as that in this study. This is somewhat encouraging in that calcareous sands have shown to be adequate materials for construction projects in geotechnical applications provided loading and/or strain level is limited to control particle breakage.

Implication for Qualitative Manufacturing of ACT Aggregates

There are several practical implications from this work related to ACT aggregate manufacturing. Firstly, it is apparent that similar to other particle breakage studies in the literature, larger particle sizes (i.e. 5-2.5PS size fraction in this study) are more susceptible to particle breakage relative to smaller size particles (2.5-1.25PS). This suggests that if aggregates manufactured by ACT as in this study were to be used in geotechnical applications in which they will be subjected to shear and/or compression conditions where the mean stresses approached or exceeded those in this research, aggregates in the 2.5-1.25PS size range would perform better than those in the 5 mm-2.5mm range. Given that the particle sizes can be controlled in the commercial aggregate manufacturing process, a move to smaller particles may be preferred in geotechnical applications, especially those in shear applications (i.e. roadways, embankment slopes). If the aggregate is to be used in applications where shear is limited and loading is predominately isotropic compression, then the amount of particle breakage is expected to be small (e.g. wide fills). For example, for the 2.5-1.25PS size, B_r values were less than 0.01 for mean stresses up to 1400 kPa in triaxial compression tests. This stress range would be above most common stress applications for urban developments.

Exposure to Freeze/Thaw Cycling

As shown in Figure 8, for f/t cycle tests carried out to only 20 cycles, resultant relative breakage was at or near that from the triaxial shear tests for the 2.5-1.25PS carbonated aggregate. This suggests that care should be taken to ensure exposure to f/t cycles is limited for this size of aggregate. However, the f/t performance of the 2.5-1.25PS size was significantly better than that of the 5-2.5PS size. For the 20 f/t cycles, limited breakage was observed. This observation should be taken within the context that 20 f/t cycles may not be representative of field applications (i.e. more f/t cycles may be present in the field). This is an area in which further testing would be useful. The manufacturing of carbonated aggregates smaller than 2.5mm appears to be desirable if f/t is a concern.

Summary and Conclusions

This paper has presented the results of various tests designed to examine the amount of particle breakage that occurs for the CKD-derived accelerated carbonated aggregate developed in this study. Of particular emphasis in this study is the role of particle size on relative breakage (B_r) for the aggregate product. Triaxial compression, triaxial shear and f/t cycling tests were performed on the carbonated aggregate using the entire grain size distribution and with isolated particle sizes (5-2.5PS and 2.5-1.25PS) to assess particle breakage. The grain sizes before and after testing were used to calculate the relative breakage, B_r. This parameter provides a fairly simple technique to provide relative comparisons between grain sizes and also allows comparisons to be made with previous studies related to calcareous sands and other more durable sands.

It was shown in this study that similar to other studies in the literature for natural soils, the majority of particle breakage in the accelerated carbonated aggregate occurred in the large particle size (5-2.5PS) relative to the smaller particle size (2.5-1.25PS). This observation was present regardless of the test method performed.

Particle breakage results from f/t testing showed that the EPS and 5-2.5PS materials corresponded to similar or slightly less particle breakage as that under triaxial shear. This suggests that environmental factors such as f/t may be as important a consideration in application to loading conditions. In contrast, the particle breakage of the 2.5-1.25PS material after 20 cycles of f/t was small and similar in magnitude to the same size aggregate under low to medium confining pressures for triaxial compression. The performance of the accelerated carbonated aggregate in terms of relative breakage (i.e. B_r) was similar or slightly better than natural calcareous sand results found in the literature but substantially higher than more durable mineral fraction sands. This is an interesting finding in that calcareous sands, although not the most desirable sand to use in construction, can be used when its geotechnical limits are known and loads and strains are limited to account for this performance. More work is required to examine these limited conditions for the accelerated carbonated aggregate, especially at higher strain levels and higher levels of f/t performance.

Figure Captions

Fig. 1. Particle size distributions for the EPS ACT aggregate sample before and after triaxial compression.

Fig. 2. Particle size distributions for the 5-2.5PS ACT aggregate sample before and after triaxial compression.

Fig. 3. Particle size distributions for the 2.5-1.25PS ACT aggregate sample before and after triaxial compression.

Fig. 4. Particle size distributions for the entire size ACT aggregate sample before and after triaxial shear.

Fig. 5. Particle size distributions for the 5-2.5PS ACT aggregate sample before and after triaxial shear.

Fig. 6. Particle size distributions for the 2.5-1.25PS ACT aggregate sample before and after triaxial shear.

Fig. 7. ACT aggregate particle size distributions, before and after 10 and 20 cycles of freeze/thaw.

Fig. 8. Relative breakage (B_r) vs Mean Stress (ρ').

Fig. 9. Comparison of B_r values in this study to literature values.

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