Experimental study of mechanical behavior of cemented light expanded clay aggregate in unconfined compression test

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ABSTRACT

Light expanded clay aggregate is a popular geotechnical backfill. By adding cementation, the light aggregate can present improved engineering performance in geotechnical engineering. This study performed unconfined compression test on cemented light expanded clay in monotonic loading way and stepped loading-unloading cycles. The results show that the peak strength increases with cement content. Loading-unloading cycles can greatly deteriorate the performance of the material, due to combined effects of particle crushing and bond breakage.

Keywords: cemented light expanded clay aggregate; bond breakage; particle crushing; peak strength; unconfined compression test

1 INTRODUCTION

Light expanded clay aggregate (LECA) is produced by pelletizing and firing clay beads in a rotary kiln. LECA has been widely used as aggregate for light-weight concrete, which can be used for partition walls, roofs and sidewalk pavement. LECA has also been widely used as geotechnical backfills behind bridge abutment or retaining wall or under road, due to its benefits including reduced earth pressure and ground settlement, and increased stability (Stoll and Holm 1985; Cheeseman and Virdi 2005; Tang et al, 2011). LECA is welcome in geotechnical engineering also because it is easy to transport, backfill and handle. The LECA particles are porous since internal pores are formed during the firing process. Some pores are enclosed while other pores are connected with outside. On LECA particle surface, the clay is melted inside the kiln and sintered into a layer of ceramic materials that is stronger than substance inside the particle. The crushing resistance of LECA particles depends on the temperature inside the kiln, the internal and surface pore volumes and sizes, the component of the raw clay and the sintering process. It is very important to avoid particle crushing in geotechnical design, which may cause significant settlement, reduced strength and lowered stability.

Bonding materials, such as cement and fly ash, can be added to the backfill, which results in a structured granular material. The geotechnical benefits of the added bonding effects are threefold. (1) Bonding materials can increase backfill strength, thus reducing the active lateral earth pressure acting on a retaining wall and increasing the passive lateral earth pressure behind a bridge abutment (Shen et al. 2016a, b, c). (2) Bonding materials can increase the integrity of the backfill. Under some condition, the light-weight LECA backfill may suffer from insufficiency of buoyancy resistance. The surface layer particles may be easily washed away during flood. When the backfill particles are glutted as a whole, the above shortcomings can be minimized. (3) Bonding material at a contact can reduce the stress concentration near the contact point and thus increase crushing resistance of LECA particles (Wong and Wu 1995).

So far, the geotechnical behavior of cemented LECA has not been well understood. In this study, unconfined compression tests were performed on cemented LECA to understand its strength and deformation behavior under uniaxial stress state. Besides, the same tests were performed on two special artificial materials: cemented steel beads and cemented Expanded Polystyrene (EPS), which are typical stiff-aggregate material and soft-aggregate material, respectively. The two additional materials were used for comparison to conceptually reveal the individual behavior of bond breakage and particle crushing at local contacts.

2 SPECIMEN PREPARATION

A commercial LECA product was used in the experiments. The bulk density of the LECA particles are 0.4 g/cm^3. Figure 1 presents the particle size distribution curve, with the particle diameter in the range of 2.0 mm to 5.0 mm. The LECA particles are sub-rounded to rounded, as shown in Figure 2 (a). The measured peak friction angle of LECA samples (void ratio = 0.8) is 40° in direct shear tests under a vertical stress of 100kPa. Besides LECA, another two types of aggregate particles were used in this study: EPS beads and steel beads. They all have the same particle size distribution as shown in Figure 1. The bulk density of EPS beads is 0.159 g/cm^3. The EPS beads are rounded in shape and the steel beads are almost perfect spheres, as presented in Figure 2 (b-c).

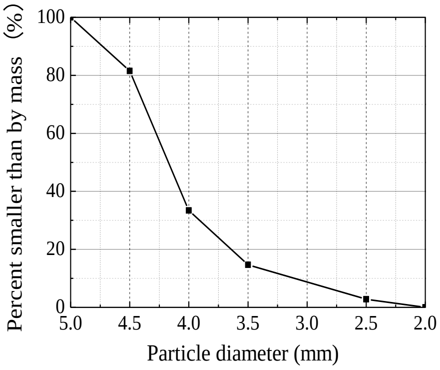


Fig. 1. Particle size distribution curve

(a) LECA particles

(b) EPS beads

(c) Steel beads

Fig. 2. Aggregates used in the tests

Two groups of specimens were prepared as follows.

(a) To prepared cemented LECA specimen, Portland cement (PC32.5R) was used as a bonding material and water was used for the hydration reaction and to facilitate the mixing process. To study the effects of bonding material content on the mechanical behavior of cemented LECA, the volume ratio of the cement over the LECA aggregate was chosen to be 2.6%, 5.6% and 9.2%, and the water-cement ratio was 0.4. The beads, water and cement were first mixed and fully stirred. The mixture was then placed into a cylinder mold with a diameter of 50 mm and a height of 100 mm. The void ratio was controlled to be 0.8, leading to three samples of different bond contents with naturally dry unit weights of 0.406, 0.53 and 0.63 g/cm^3, respectively. After a curing period of 7 days, unconfined compression tests were performed with a loading rate of 0.6%/min, as shown in Figure 3.

(b) The same procedures were followed to prepared cemented EPS and steel beads. The cement-aggregate volume ratio is 5%. The void ratio was controlled to be 0.8, too. The naturally dry unit weights of cemented EPS and steel bead samples are 0.2 and 5.06 g/cm^3, respectively. This group of specimens were used to study the effects of aggregate stiffness on mechanical behavior of cemented aggregate.

Fig. 3. Unconfined compression test on cemented LECA

3 BEHAVIOR OF CEMENTED LECA IN UNCONFINED COMPRESSION TEST

Figure 4 presents the stress-strain curves of cemented LECA in unconfined compression tests. The axial stress first increases with the axial strain in an almost linear way, followed by a sharp drop after the peak state. In practice, the cemented LECA's stress should be controlled to avoid abrupt failure. The specimens did not abruptly break into pieces after peak. Instead, after the sharp drop, the specimen can still take a residual stress with further axial strain. The peak strength increases with cement content. However, it is interesting to note that the slope of the linear part is virtually independent of the cement content.

Microscopically, it is observed that the added cement mainly covers aggregate surfaces and bonds neighbor aggregates. It is possible that the inter-aggregate bond contact number does increase with the cement content. Instead, the increase in cement content mainly (1) increases the thickness of cement layer covering aggregate surfaces which does not influence the macroscopic behavior of cemented LECA, and (2) leads to the increase of cement volumes at bond contacts, thus leading to increased peak strength. The increase of cement volume at contact is expected to increase contact stiffness and as a result to increase the macroscopic modulus. However, this is not observed from Figure 4. Figure 5 presents the photo of a failed cemented LECA specimen in unconfined compression test. On the rupture plane, about 30% of the failure points are due to particle crushing and the rest 70% are due to contact-point bond breakage. It is possible that particle crushing hinders the expected increase of modulus with cement content. This is explored in the next section.

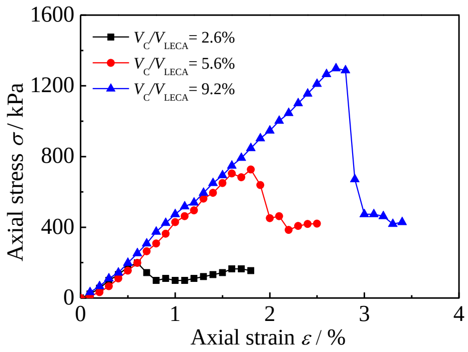


Fig. 4. Effects of cement content on behavior of cemented LECA in monotonic unconfined compression tests

Fig. 5. Cemented LECA specimen after failure in monotonic unconfined compression test

Figure 6 presents the stress-strain curves of cemented LECA in unconfined compression tests in two different loading modes: monotonic loading and stepped loading-unloading cycles. In the loading-unloading cycles, significant residual deformation is observed when the axial stress reduces to zero. The average slope of the unloading-reloading path in each cycle, $E_{u\text{-}r}$, is markedly greater than the slope of the monotonic loading, E_m. It is also interesting to note that the upper envelope of the curve from the loading-unloading cycles has a slope smaller than the monotonic loading slope. The peak strength of the specimen experiencing loading-unloading cycles is about half of the strength in the monotonic loading. The overall behavior becomes more ductile with loading-unloading cycles than in the monotonic loading situation. Loading-unloading stress path would deteriorate the behavior of cemented LECA greatly and alter the specimen failure modes from inclined rupture plane sliding in Figure 5 to vertical splitting as shown in Figure 7. It is necessary to consider this effect in geotechnical backfill design. The question raises: is the deterioration due to particle crushing, which is easier for LECA than sands, or due to bond breakage that is common for all structured granular material (including structured sand)? This is explored in the next section.

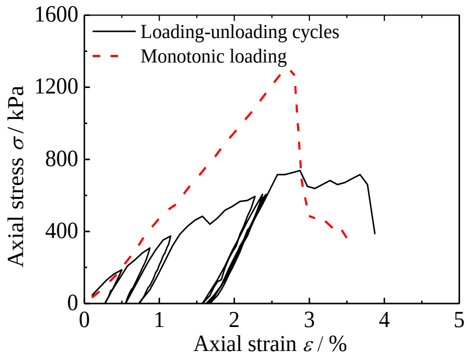


Fig. 6. Stress-strain curves of cemented LECA in monotonic unconfined compression test and under loading-unloading cycles.

Fig. 7. Failed cemented LECA specimen after experiencing loading-unloading cycles.

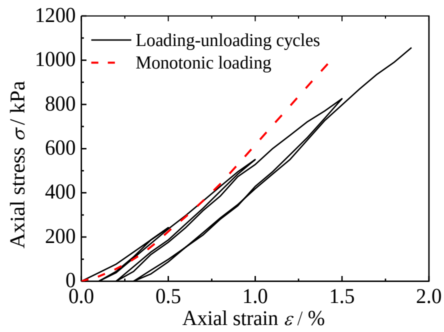
4 EFFECTS OF AGGREGATE PROPERTY ON CEMENTED SPECIMEN BEHAVIOR

Figure 6 and 8 show that the three artificial cemented granular materials present distinct uniaxial compressive behavior.

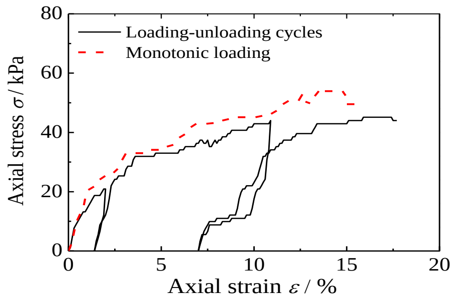
In Figure 8(a), for the monotonic loading, the stress-strain curve of cemented steel beads presents an increase in the tangent slope. This resembles the Hertz contact behavior between two ideal elastic spheres. In Figure 8(b), for each loading-unloading cycle, residual strain is observed after each cycle purely due to contact bond breakage since the steel beads will not break in the test condition. Despite the presence of bond breakage, the upper envelope of the loading-unloading curve exhibits an increase in tangent slope with axial strain, as observed in the monotonic loading test. For cemented steel beads, the difference between the upper envelope of the loading-unloading curve and that in the monotonic loading is much smaller than the cemented LECA.

In Figure 8(b), the cemented EPS beads present a stepwise hardening behavior. The tangent slope of the stress-strain curve generally decreases gradually as the axial strain increases and the response is ductile and highly nonlinear. The monotonic loading curve lies above the loading-unloading curve, as observed with cemented LECA and steel beads.

Particle crushing was observed in cemented LECA but was not found in cemented EPS and steel beads. The LECA particle's stiffness lies between the other two extremes (steel and EPS beads). The different patterns of observed behavior of the three tested cemented materials are believed to origin from the different particle stiffness and robustness. These differences also lead to distinctive sample failure modes as shown in Figure 9. Discrete Element Method (DEM) simulation will be used in future research to explore the related micro-mechanism.



(a) Cemented steel beads



(b) Cemented EPS beads

Fig. 8. Stress-strain curves of cemented EPS beads and steel beads in monotonic unconfined compression tests and under loading-unloading cycles.

5 CONCLUSIONS

This study focused on the mechanical behavior of cemented LECA in unconfined compression test. As expected, the uniaxial peak strength of the cemented LECA increases with cement content. However, the deformation modulus does not depend on cement content. Loading-unloading cycles can greatly deteriorate the performance of the material by reducing the peak strength and modulus but increasing the ductility. Comparison are made with two reference materials: cemented steel beads with very large contact stiffness and cemented EPS beads with very low contact stiffness. The comparison indicates that it is the combined effects of particle crushing and bond breakage that leads to the peculiar behavior of cement LECA. The results should draw the attention of geotechnical engineers to take into consideration the loading path and loading history effects in the lifetime of cemented LECA. Severe deterioration of its mechanical perform may be encountered.

(a) Cemented steel beads (b) Cemented EPS beads

Fig. 9. Failed specimens in monotonic loading.

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