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Mechanical behaviour of cement-treated sand

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HIGHLIGHTS

- We investigated the compressive and tensile behaviour of cement-treated sand.
- Compressive strength of cement-treated sand is independent of test specimen size.
- Compression and tension softening behaviour of cement-treated sand are investigated.
- Compression fracture zone length of cement-treated sand is approximately 250 mm.
- Relationship between compressive and tensile fracture energy are suggested.

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ABSTRACT

A study has been conducted to investigate the mechanical behaviour of cement-treated sand under compression and tension. Cylindrical and notched beam specimens were made by using high early strength cement, sand, and limestone powder with varying ratios of water to cement (W/C), specific ratios of cement to sand (C/S), and limestone powder to cement (L/C). The influences of the material strength and height to diameter ratio (H/D) on the compressive and tensile strength, as well as the fracture energy were investigated. Stress strain relationships are proposed to predict the behaviour of cement-treated sands.

1. Introduction

Problematic soils have been historically ignored in favour of higher quality soils with fewer technical difficulties and construction costs. Alternative construction methods have become important in recent decades, due to the unavailability of high quality soil for construction. Soil improvement techniques can enhance the mechanical behaviour of soil by reducing the permeability and improving compaction. The type of stabiliser used depends on the treated soil; for sandy soils, cement is preferred, while for clayey soils, lime is the preferred stabiliser due to the mineral composition of the clay. Soil cementation can be found naturally or induced artificially to improve the engineering characteristics of soil. Ground improvement via cement addition has been used for structural foundations, excavation control, and liquefaction mitigation.

The cement content increases the peak strength and stiffness of the treated soil; increasing the stiffness of the treated soil lowers the strain threshold at which failure occurs. Therefore, cement causes failure to be more brittle and catastrophic under drained conditions [1]. Addition a small quantity of cement (up to 2%) can modify the properties of the soil, but adding more cement may cause the failure to be brittle and may significantly change the mechanical behaviour of treated soil [2]. The viscosity of the cement-based material can be improved by decreasing the water/cementitious material ratio or by using a viscosity-enhancing agent. This property can also be improved by increasing the cohesiveness of the paste by adding a filler material, such as limestone powder. Using limestone powder improves the properties of fresh and hardened concrete, including workability and durability [3]. At a fixed water content, a high powder volume increases the interparticle friction due to the increased solid–solid contact, possibly affecting the ability of the mixture to deform under its own weight and pass through obstacles [4].

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To improve the earthquake performance of a foundational structure in soft ground, the horizontal resistance of the ground must be increased. The composite ground foundation technique under development in Japan is a new type of foundation that remarkably improves the horizontal bearing capacity by considering the mechanical interactions of the improved ground and pile. The actual application of the composite ground method is being investigated in road construction projects, such as the Ariake sea coastal road and the Tokyo-Gaikan expressway Japan, using laboratory model tests and in situ loading tests [5,6]. However, design methods vary in different construction sites, depending upon the scope of the ground improvement, and the deformation characteristics of the soil.

When using cement-treated sand around existing/newly built pile foundation, the mechanical behaviour of the cement-treated sand around the structural members (piles) may influence the seismic behaviour of pile foundation. In these cases, localised deformations or failures in cement-treated soil do not always limit the capacity of the foundation, leaving sufficient capacity even after a localized failure of the cement-treated sand. Therefore, to evaluate the seismic performance of a structure, accounting for the post-peak (softening) behaviour of cement-treated sand is important.

Spatially averaged numerical simulations, such as the finite element method, are often used to evaluate the seismic performance of structural systems including soil and foundations.

During finite element modelling, various element sizes can be used depending on the size and shape of the targeted structural members. When the post-peak (softening) behaviour of the materials is considered, the post-peak descending curve should depend on the size of the finite element and consider the energy equilibrium. Therefore, the fracture energy may be a unique material parameter, defining the post-peak descending curve of the stress–strain relationship based on the element size and energy equilibrium during compression and tension [7,8].

In this paper, the compression and tensile fracture energy of cement-treated sand, as well as contribution of the characteristics toward modelling the softening behaviour of cement-treated sand were investigated.

2. Materials and methods

2.1. Materials

High early strength cement, limestone powder, and sand were used to make the test specimens. Poorly graded, oven dried sand (uniformly graded) that had passed through a 5 mm sieve was used. The sand had coefficients of uniformity and curvature of 2.2 and 1.0, respectively. These parameters were calculated according to the Unified soil classification system [9]. The sand absorbed 1.32% water. The particle densities of the sand, cement, and limestone powder were 2.63, 3.16, and 2.70 g/cm^3, respectively. Limestone powder was used to increase the viscosity of the paste and to increase the workability of the mix. The moisture already present in the limestone powder was ignored during the mix design. A sieve analysis of the sand and limestone powder is shown in Fig. 1.

2.2. Mix proportions

The test variables included ratios of water to cement (W/C) 100%, 130%, 150%, 170%, 190%, cement to sand (C/S) 30%, and limestone powder to cement (L/C) 130% by weight. These ratios were selected after preliminary experiments. The W/C was varied to study the failure mechanism of high strength and relatively weak cement-treated sand. The composition of cement-treated sand used during the tests is described in Table 1. First, the sand was mixed with the limestone powder; afterward, cement and finally water were added to the mix. Curing was performed by covering the specimens with wet cloths. The density of specimens was approximately 2100 kg/m^3.

2.3. Specimens and testing methods

2.3.1. Unconfined compression test

Cylindrical specimens 100 mm and 150 mm in diameter (D) were produced with various heights (H) according to H/D ratios from 1 to 4. Unconfined compression tests were performed for curing periods of 7 and 14 days. The experiments were carried out under controlled loading conditions, and the total average strain for the uniaxial compression test was measured externally using transducers set between the loading plates.

To investigate the internal behaviour of the cement-treated sand during compression, strain gauges were attached to custom-made silicone bars that were placed at the centre of the specimens and kept straight using the wires from the strain gauges. Silicone is less stiff (Young's modulus of approximately 0.4 GPa) than cement-treated sands and therefore exerts little effect on the strain gauge (Fig. 2). Finally, 144 and 21 specimens were tested to determine the compressive strength and compression fracture zone length, respectively.

2.3.2. Splitting tension test and notched beam test

Cylindrical specimens (150 × 150 mm) were produced to assess the splitting tensile strength and experiments according to ASTM [10]. Beam specimens (100 × 100 × 400 mm) with a 30 mm central notch were produced to measure the tensile fracture energy (G_{ft}); three point bending tests were carried out [11], as shown in Fig. 3. Ten and 25 specimens were tested to determine the splitting tensile strength and fracture energy, respectively.

3. Test results and discussion

3.1. Behaviour during compression

3.1.1. Peak stress, strain, and Young's modulus

The uniaxial compressive strength for the cement-treated sand cured for 14 days is summarised in Table 2. The strength developed during the curing time for W/C ratios of 130% and 150% are shown in Figs. 4 and 5, respectively.

The maximum compressive stress is independent of the size of the cement-treated sand test specimens. The average strain corresponding to the peak stress (14 days) for these cement-treated sands was approximately 0.003 (Fig. 6).

Young's modulus (E_o) for a specimens 100 mm in diameter using W/C = 100% that was cured for 14 days was approximately 6 GPa when calculated according to ASTM [12] (Fig. 7).

Based on the test results, an empirical relationship between the uniaxial compressive strength and Young's modulus for cement-treated sand is suggested (Fig. 8):

$$E_o = 0.8f_c^{0.7} \qquad (1)$$

where f_c is the uniaxial compressive strength in MPa and E_o is Young's modulus in GPa.

The normalised stress–strain curve over the 14-days curing period for specimens 100 mm in diameter where W/C = 130% is shown in Fig. 9. The behaviour of the cement-treated sand was initially linear, becoming nonlinear at high strain levels. The softening behaviour varies with the different specimen heights due to the compression fracture zone length. For specimens where H/D = 1, more softening occurs after peak stress compared to the others because the compression fracture zone length of the cement-treated sand extends beyond the 100-mm height. This phenomenon is explained in Section 3.1.3.

3.1.2. Failure patterns of the specimens

Soil generally fails in shear under compressive load; therefore, the soil strength is primarily a function of shear strength. However, the normal concrete failure mode is usually cone-shaped [13]. Cone and split failure modes were observed for the cement-treated sand. The failed specimens 100 mm in diameter and 300 mm tall with different W/C ratios are shown in Fig. 10.

3.1.3. Compression fracture zone length, L_p

When concrete fails, the damage is usually concentrated in a narrow region of the structure. This localisation can influence the structural behaviour, particularly the post-peak behaviour. Therefore, the fracture zone and the localisation behaviour must be clarified to understand the structural behaviour up to failure. The strain softening of concrete occurs when microcracks that began