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Behavior of Cement Treated Sand under Cyclic Compressive Stress

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Abstract: The ground improvement technique is gaining popularity but the strength deformation behavior of improved soil under uniaxial loading over the long term and its structure is not well understood. The purpose of this study is to understand the behavior of cement treated sand under cyclic compressive stress. Cylindrical specimens were casted by using high early strength cement, sand and limestone powder for water to cement ratio (W/C) of 100%, 130%, 150%, 170% and 190 %, cement to sand ratio (C/S) of 30%, limestone powder to cement ratio (L/C) of 130% to investigate the softening behavior of cement treated sand under cyclic compressive stress. Limestone powder was used to increase the viscosity of the mix. The influences of material strength and height to diameter ratio (H/D) on Compressive strength and Stress strain relation are investigated. Relationship between Unconfined compressive strength and Young's Modulus; and stress strain relationship is suggested which will be helpful in predicting the behavior of cement treated sands.

1. INTRODUCTION

Soils are the oldest and cheapest abundantly available complex natural engineering material used as a foundation or construction material. The properties of foundation soil can be improved by using ground modification techniques such as compaction, addition of cement etc. Problematic soils have been ignored for long time in favor of more quality soils with reduced technical difficulties and lower construction costs. Alternative areas for construction have become important during the last decades, due to non availability of better quality soils for construction. These limitations can be resolved by improving the engineering properties of soils.

Soil improvement may be permanent or temporary depending on the purpose for which it is used. Type of stabilizer depends on the treated soil, for example for sandy soils cement is preferred and for clayey soils lime is preferred to be used as a stabilizer because of their mineral composition. Ground improvement by cement mixing have been applied extensively for structure foundation, excavation control and liquefaction mitigation. By using soil improvement techniques density, shear strength are increased while compressibility, settlement and permeability are reduced making the soil more stable and durable.

Porbaha et al. (2002) describes that the mechanical properties of most cement stabilized soils change over time; therefore the time-related performance of such treated soils is essential in understanding their durability and long-term effectiveness. Cementation plays a significant role in the mechanical behavior of soils, and it has been investigated by researchers around the world. Abdullah et al. (1997) describes that the cohesion of cemented sand increases non-linearly with cement content. Addition of small quantity of cement upto 2% can modify the properties of the soil as observed by Bell (1993) but addition of more cement will cause the failure to be brittle and will significantly changes the mechanical behavior of treated soil. This effect of cementation of soil has been considered by many researchers. Lee et al. (2002) observed that the cement content does increase the peak strength of the treated soil, it also increases the stiffness thereby reducing the strain at which failure occurs.

The viscosity of cement-based material can be improved by decreasing the water/cementitious material ratio or using a viscosity-enhancing agent. It can also be improved by increasing the cohesiveness of the paste through the addition of filler, such as limestone powder. Zhou et al. (2010) observed that the use of limestone powder improves the properties of fresh and hardened concrete such as workability and durability. However, excessive addition of fine particles can result in a considerable increase in the specific surface area of the powder, which results in an increase of water demand to achieve a given consistency. Nawa et al. (1998) noted that for fixed water content, high powder volume increases interparticle friction due to solid–solid contact. This may affect the ability of the mixture to deform under its own weight and pass through obstacles.

A generally accepted behavior of concrete under cyclic loading is that an envelope curve, which provides a bound between the upper limit and lower limit for the stress strain curve, can be obtained under different loading paths. Experiment performed by Bahn et al. (1998) showed that the existence of an envelope curve for a concrete can be studied by comparing test results of cycles to envelope curve with the corresponding test results of monotonic loading.

For concrete the unloading stiffness is not constant, therefore for the concrete it is important to take into account a factor which represents the concrete non linearity and the degree of accumulated mechanical damage of concrete. According to Okamura et al. (1991), non linear factors in concrete can be explained with the concept of the disappearance of a volume of the constituent material of concrete which has the ability to reserve the elastic strain energy and such degradation in the capacity to absorb elastic energy is defined as “fracture”. The effect of fracture appears directly in the decrease of the unloading or reloading stiffness.

Okamura et al. (1991) proposed modeling of concrete under uni- and multi-axial stress state based on plasticity and fracture theory. The fracture parameter (K) represents the degree of the fracture and is defined as the ratio of constituent elements which maintain the abilities to support the stress. It is formulated as the ratio of unloading stiffness (E_u) to initial stiffness (E_o). The value is equal to unity within elastic range. The constitutive model for concrete suggested in standard specification of concrete structures by JSCE (2002) is as follows:

[1] $$\partial_c = E_o K(\varepsilon'_c - \varepsilon'_p)$$

Where

[2] $$E_o = \frac{2f'_{cd}}{\varepsilon'_{peak}}$$

[3] $$K = \exp\left\{-0.73\frac{\varepsilon'_{max}}{\varepsilon'_{peak}}\left(1-\exp\left(-1.25\frac{\varepsilon'_{max}}{\varepsilon'_{peak}}\right)\right)\right\}$$

[4] $$\varepsilon'_p = \varepsilon'_{max} - 2.86.\varepsilon'_{peak}\left\{1-\exp\left(-0.35\frac{\varepsilon'_{max}}{\varepsilon'_{peak}}\right)\right\}$$

∂_c is uniaxial compressive stress, ε'_c is the average axial strain for given axial load, ε'_p is the plastic strain which is defined as the residual uniaxial strain at zero stress, ε'_{max} is the maximum strain in each loading cycle, E_o is modulus of elasticity, f'_{cd} is the design compressive strength, ε'_{peak} is the strain corresponding to unconfined compressive strength and K is fracture parameter as shown in Figure 1.

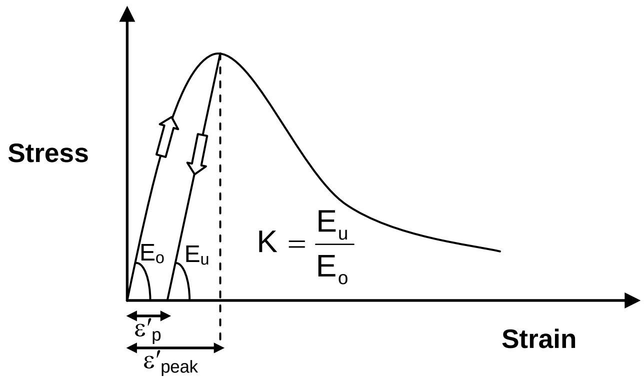

Figure 1: Plastic strain (ε'_p) and Fracture parameter (K) explanation

Lambe et al. (1969) describes that when a dry soil is vertically compressed the deformation in immediate vicinity of the contact points of particles will be elastic or plastic strain. Soft/weak soils are very complex and much advancement has been made in recent years regarding the constitutive modeling of soil. For Cement-treated soil, microscopic fracture may occur in the material due to the existence of cement hydrates in between soil particles, results in the reduction in capacity of elastic energy absorption which is modeled as a reduction in the reloading stiffness proposed by Okamura et al. (1991).

In this paper an attempt has been made to model the pre- and post-peak mechanical behavior of cement-treated sand based on both plasticity and fracture theory and behavior under cyclic compressive stress is investigated.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

High early strength cement, limestone powder and sand were used to make the test specimens. Test variables were W/C = 100%, 130%, 150%, 170%, 190%, C/S = 30%, and L/C = 130% by weight. These ratios were selected after trial experiments. W/C is varied in order to study the failure mechanism of high strength and relatively weaker cement treated sand. Poorly graded sand (uniformly-graded) passing 5mm sieve was used having coefficient of uniformity and curvature about 2.2 and 1.0 respectively which was calculated according to ASTM D2487 (2006) Unified soil classification system.

The water absorption of sand was 1.32%. The density of sand, cement and limestone powder was 2.63, 2.70 and 3.16 g/cm^3 respectively. The diameter of specimens was kept constant as 100 and 150mm, and H/D ratio is varied from 2 to 4 in order to investigate the size effect on unconfined compressive strength of cement treated sand. Curing is done by covering the specimens with wet clothes. Unconfined compression test were performed for curing period of 7 and 14 days. The density of specimen was about 2100 kg/m^3. Sieve analysis of sand and limestone powder is carried out in accordance with ASTM D6913 (2004) as shown in Figure 2.

Sand was first mixed with limestone powder; then with cement and finally water was added to the mix. Limestone powder was used to increase the viscosity of the paste and to make the mix more workable. The moisture already present in the limestone powder was ignored in the mix design. The experiments were carried out under controlled loading conditions and the total average strain for uniaxial compression test was measured externally by using transducers that were set between loading plates.

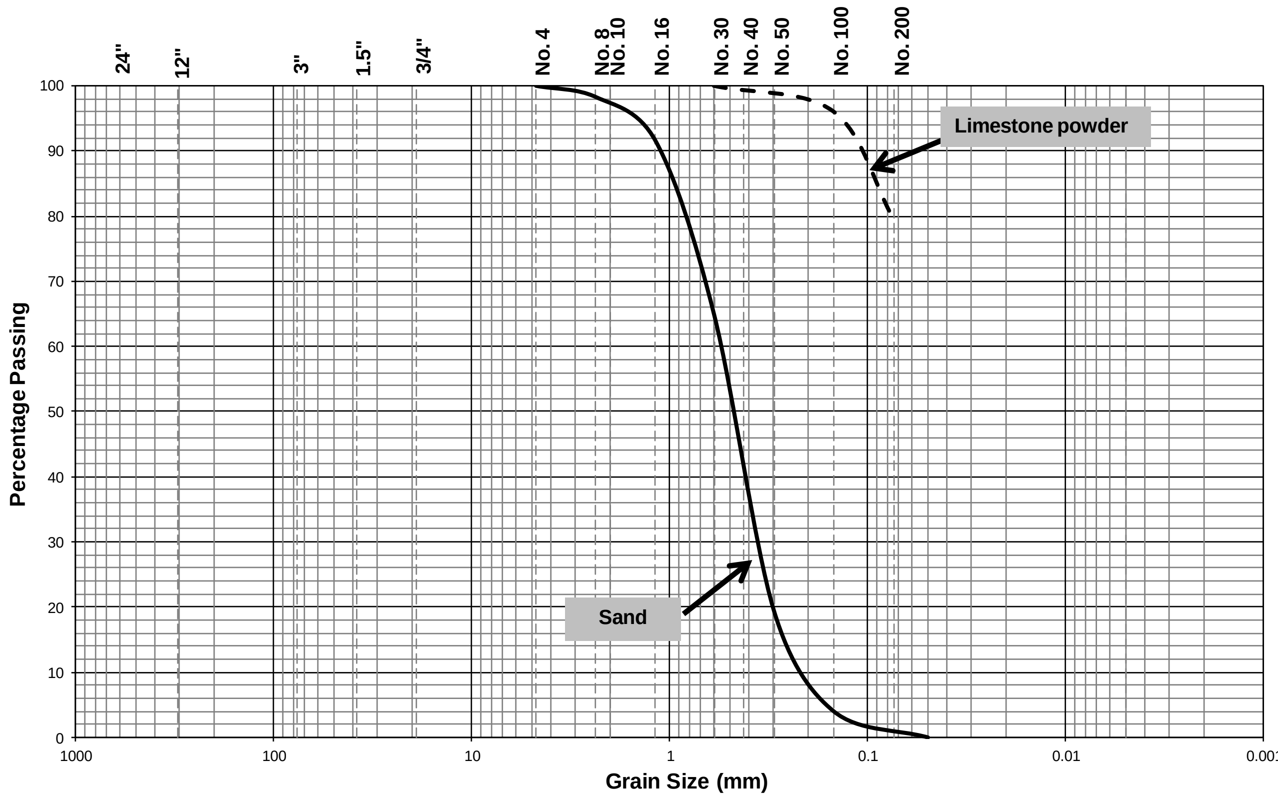

Figure 2: Sieve analysis of sand and limestone powder

3. TEST RESULTS AND DISCUSSIONS

Though, cement treated sand can bear compressive load but due to its plastic nature it undergoes volume change while performing compression test. Therefore, area correction was applied while calculating compressive strength of such cement treated sands. Corrected area, A is calculated according to JGS0511 (2000) and is given as:

[5] $$A = \frac{A_o}{(1-\varepsilon)}$$

A_o is initial average cross-sectional area, ε is the average axial strain for given axial load (expressed as decimal) and it is calculated as:

[6] $$\varepsilon = \frac{\Delta H}{H_o}$$

H_o is initial height of test specimen and ΔH is change in height of specimen.

Development of strength of specimens with curing time for W/C ratio of 130, 150 and 170% is shown in Figure 3 and 4. It can be seen from the results that the unconfined compressive strength is independent of the size of the test specimens for cement treated sands. The results for 14 days curing period are summarised in Table 1.

Table 1: Unconfined compressive strength (MPa) for different W/C ratios and diameter

W/C	Specimen size D X H (mm)					
%	**100 x 200**	**100 x 300**	**100 x 400**	**150 x 300**	**150 x 450**	**150 x 600**
100	20.14	18.89	17.98	18.76	-*	-*
130	10.37	10.13	9.38	9.12	9.19	10.59
150	6.65	6.96	6.06	6.18	5.18	5.28
170	4.81	4.36	4.12	3.71	3.56	3.42
190	3.47	3.76	3.71	3.17	-*	-*

-* specimen not casted

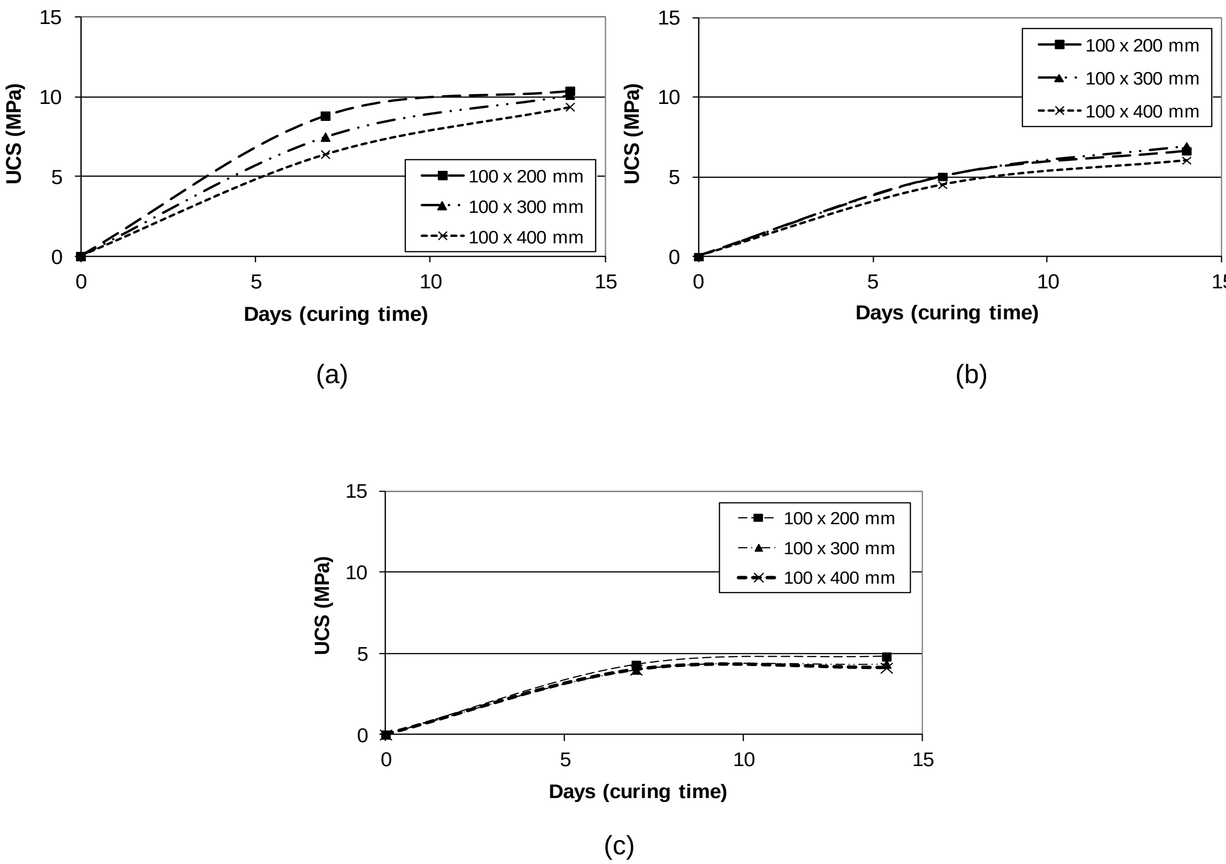

Figure 3: Comparison of unconfined compressive strength (UCS) for specimen having diameter 100 mm for W/C = (a) 130% (b) 150% (c) 170%

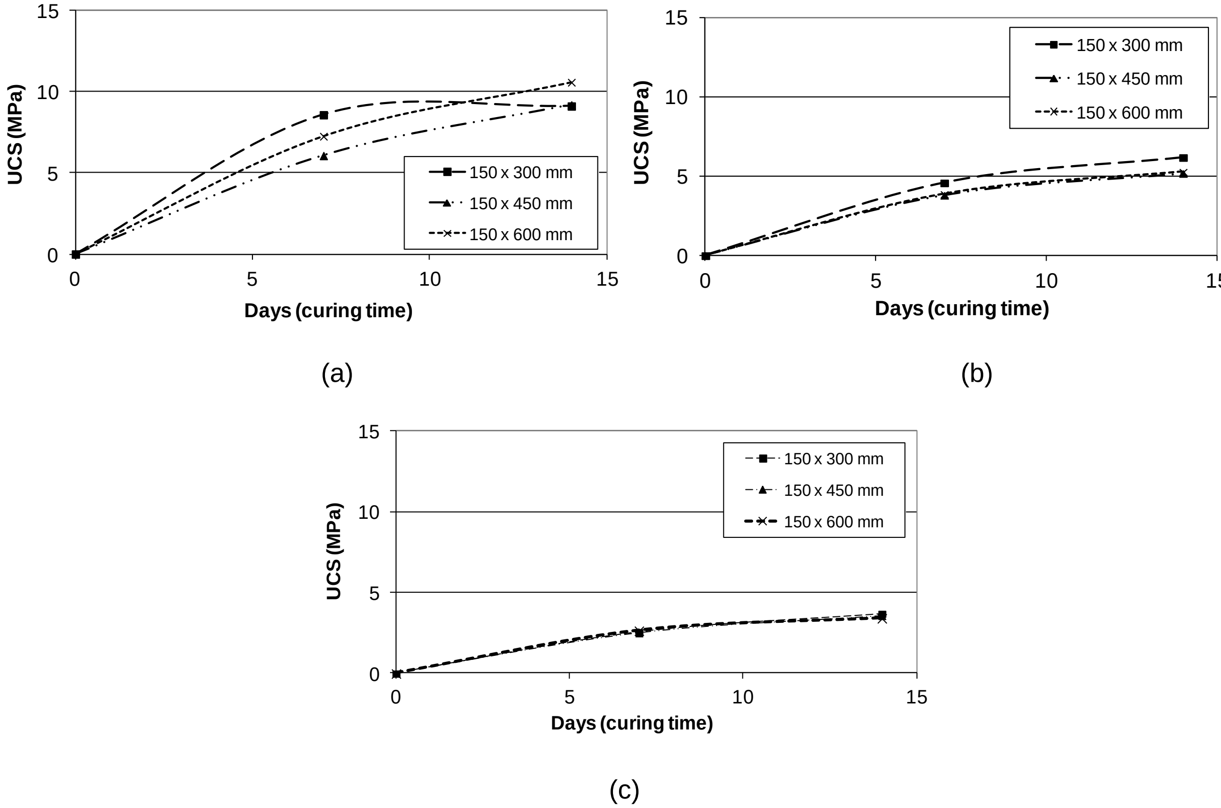

Figure 4: Comparison of unconfined compressive strength (UCS) for specimen having diameter 150 mm for W/C = (a) 130% (b) 150% (c) 170%

Strain corresponding to unconfined compressive strength (14days) for such cement treated sands is about 0.003 (Figure 5a). Young's modulus (E) for 14 days curing period for specimen having 100 mm diameter using W/C = 100 % is about 6 GPa (Figure 5b).

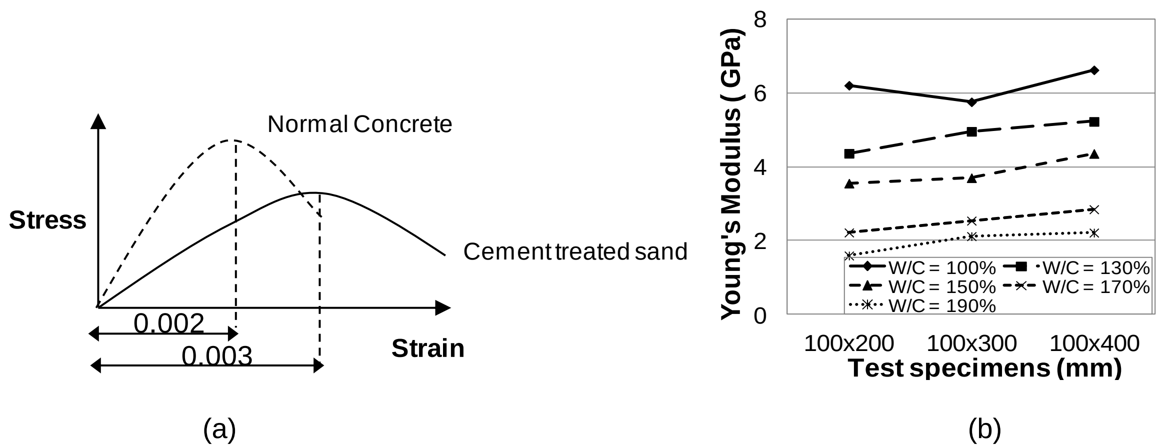

Figure 5: (a) Schematic stress strain curve showing peak strain at UCS (b) Young's Modulus for different W/C ratios

Based on the test results, an empirical relationship between Compressive strength and Young's modulus for such cement treated sand is suggested (Figure 6):

[7] $$E_o = 0.36 f_c^{1.1}$$

Where, f_c is Unconfined compressive strength in MPa and E_o is Young's modulus in GPa.

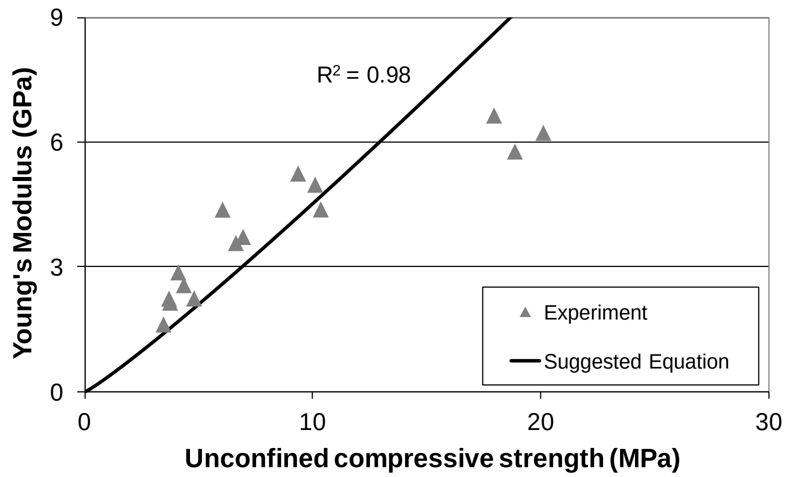

Figure 6: Unconfined compressive strength ~ Young's Modulus

In order to understand the behavior of cement treated sand subjected to cyclic loading, uniaxial cyclic compression test was carried out as shown in Figure 7.

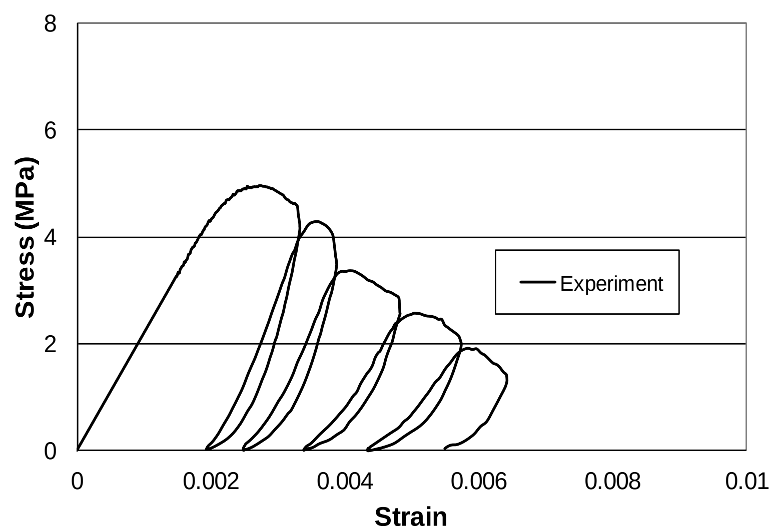

Figure 7: Uniaxial cyclic loading test on 150 x 450 mm specimen of W/C = 150%

Plastic and fracture behavior of such cement treated sand is analyzed using existing model of concrete and their respective models are suggested. Graphical representation of equation proposed for estimation of plastic strain and fracture parameter for 100 x 300, 100 x 400 mm specimens is shown in Figure 8 and 9 respectively. Strain is normalized with the peak strain (ε'_{peak}) because peak strain also depends on the W/C ratio.

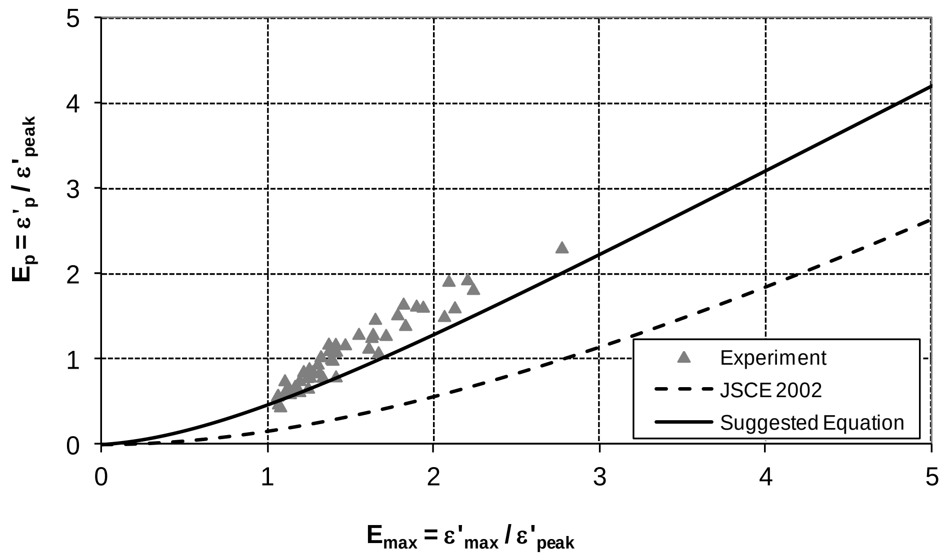

Figure 8: Suggested equation for plastic strain

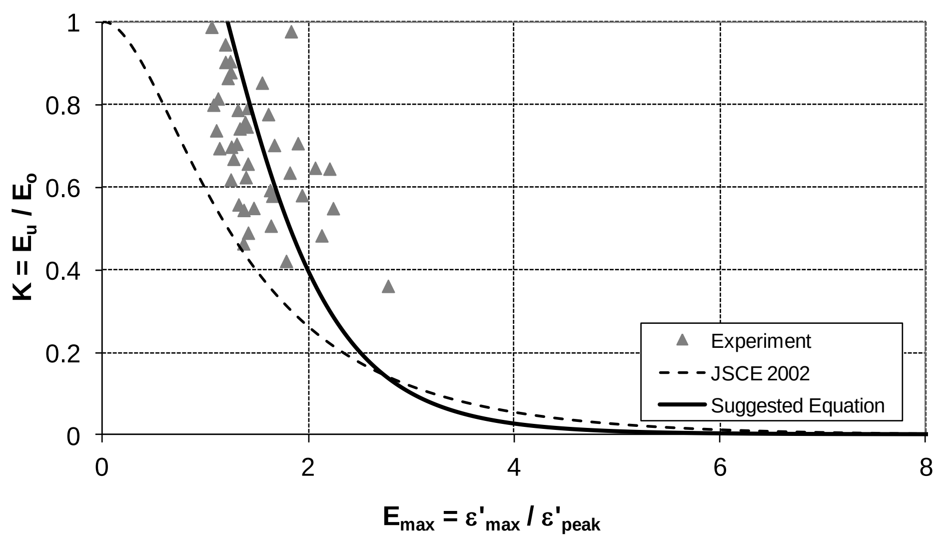

Figure 9: Suggested equation for fracture parameter

Young's Modulus, Plastic strain and Fracture parameter of such cement treated sand can be estimated using following proposed equations:

[8] $$E_o = \frac{1.5f'_{cd}}{\varepsilon'_{peak}}$$

[9] $$K = \exp\left\{-2.6\frac{\varepsilon'_{max}}{\varepsilon'_{peak}}\left(0.4 - \exp\left(-0.75\frac{\varepsilon'_{max}}{\varepsilon'_{peak}}\right)\right)\right\}$$

[10] $$\varepsilon'_p = \varepsilon'_{max} - 0.8.\varepsilon'_{peak}\left\{1 - \exp\left(-1.1\frac{\varepsilon'_{max}}{\varepsilon'_{peak}}\right)\right\}$$

Suggested stress strain relationship of such cement treated is shown in Figure 10 and difference between the actual unloading stiffness of cement treated sand with the predicted skeleton curve of Figure 10 is shown in Figure 11. It can be seen that using suggested equations for young's modulus, plastic strain and fracture parameter predicts well the stress ~ strain behavior of cement treated sand.

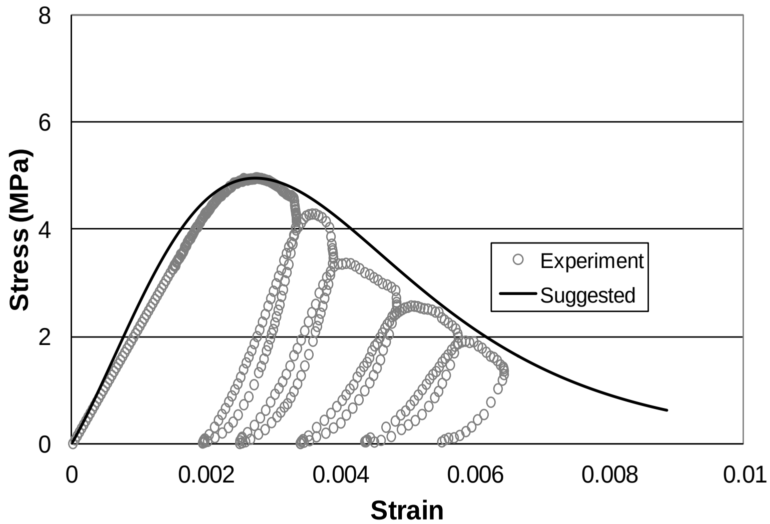

Figure 10: Suggested stress strain relation for 150 x 450 mm specimen (W/C = 150%)

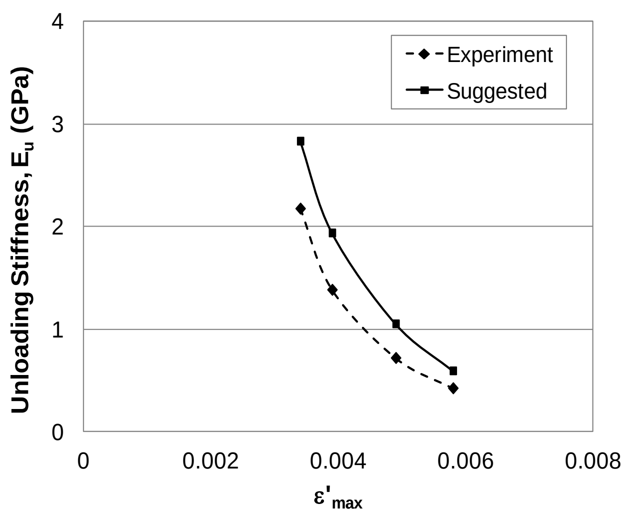

Figure 11: Actual unloading Vs Predicted unloading stiffness

4. CONCLUSIONS

A series of uniaxial cyclic compression tests were carried out in order to investigate the mechanical behavior of cement-treated sand. Based on the test results of selected mix proportions, following are the conclusions:

- Uniaxial compression tests were performed for specimens by varying H/D ratio from 2 to 4. Test results have indicated that unconfined compressive strength of cement-treated sand is independent of the size of the test specimen.
- Unconfined compressive strength is about 20, 10, 7, 4.5 and 3.5 MPa for W/C = 100, 130, 150, 170, 190 % respectively.
- Strain corresponding to unconfined compressive strength is about 0.003.
- Young's Modulus is about 6, 5, 4, 2.5 and 2 GPa for W/C = 100, 130, 150, 170, 190 % respectively.
- A constitutive model based on both plasticity and fracture theory, and empirical relations are proposed to describe the behavior of cemented treated sands.

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