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STRENGTH AND BEARING CAPACITY OF ARTIFICIALLY CEMENTED SANDS

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SYNOPSIS

The strength and bearing capacity of artificially cemented sands were examined by laboratory triaxial and model footing tests. Ordinary Portland cement in the amount of 1% by weight was used as an additive to produce a weakly cemented sand. Drained isotropically consolidated triaxial compression tests, and model strip footing tests were carried out on the cemented sand to determine its strength characteristics c, ϕ and the ultimate bearing capacity and the failure mode of shallow footings. The results are compared with similar tests on uncemented sand of identical origin and relative density. The results indicated that the angle of friction ϕ is not affected by cementation. However, a cohesion intercept, c, of 25kPa is produced by cementation which led to a significant increase in bearing capacity. Cemented sand displayed a stiff response characterized by larger soil modulus and small footing settlement under load. The conventional bearing capacity formula is used for weakly cemented sand for prediction of the bearing capacity.

INTRODUCTION

Cemented sands exist in many places of the world where arid conditions prevail. The cementing agents are usually carbonates, hydrous silicates, iron oxides, and gypsum. High temperature, and dessication cause additional interparticle bonding which may be eliminated on saturation. The degree of cementation ranges from weakly cemented to very strongly cemented depending on the amount of the cementing agent, type and history of the deposit, and the overburden pressure. At the same location, the degree of cementation may vary with depth. The soil profile in the State of Kuwait consists of extensive cemented sand deposits at many locations which are frequently overlain by a layer of cohesionless, fine windblown dune sand.

In an effort to characterize the properties and behaviour of cemented sands, several laboratory testing programs were carried out recently on naturally ce-

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mented undisturbed block samples and on artificially cemented sand using Portland cement as an additive. Tests included triaxial compression, and consolidation tests, (Clough et al., 1981, Ismael et al., 1986, Allman and Poulos 1988). These tests revealed that cemented sands possess a cohesion intercept, c, and a slight or no increase in the angle of friction ϕ, However, the residual shear strength parameters are similar for cemented and uncemented sands of the same relative density. Artificially cemented samples were occasionally employed under controlled conditions in the laboratory to save the effort required to obtain undisturbed samples of cemented sands. Although cemented sands in the form of soil-cement mixes have often been used in practice to replace unsuitable soil layers below the foundation level, no attempt has been made to examine, by field or laboratory model tests the bearing capacity and compressibility of these soils.

To provide a good understanding of the strength and bearing capacity of weakly cemented sands, a laboratory testing program was carried out on artificially cemented calcareous sand. The program included drained triaxial compression tests and model tests on a rectangular footing 51 × 305 × 51mm thick. The cementing agent employed was ordinary Portland cement in the amount of 1% by weight. All tests were carried out on samples prepared at a relative density of 66% which is similar to the insitu condition of the near surface deposits at many sites in Kuwait, (Ismael et al., 1987). This paper presents and analyzes test results and compares it with similar tests on uncemented sand compacted to the same relative density, (Ismael and Ahmad, 1989).

SOIL PROPERTIES AND TRIAXIAL TESTS

The sand employed in this program was recovered from Jabriya, Kuwait. A large bulk sample weighing approximately 19kN (1 ton) was transported to the laboratory for use in the triaxial and model tests. This sand has been previously described, (Ismael and Ahmad, 1989) as predominantly fine, calcareous, cohesionless windblown sand. Chemical analysis on representative samples indicated that the silica content is 75% and the amount of carbonates is 18.2% mostly in a form of calcium carbonate. A summary of the physical properties of the sand is given in Table 1.

Table 1 Classification properties of the test sand after Ismael and Ahmad (1989)

Coefficient of Uniformity	4.4
Mean Diameter (mm)	0.21
Specific Gravity	2.71
Maximum Density (Mg/m^3)	1.846
Minimum Density (Mg/m^3)	1.596

Specimens for the triaxial tests were prepared by mixing the sand with 10% water and 1% of ordinary Portland cement. The soil was poured into standard laboratory brass tubes and was tamped in layers to yield samples 73mm diameter and 150mm height, and a relative density of 66%. The samples were cured for 28 days at room temperature and 100% humidity prior to testing.

Isotropically consolidated drained (CID) triaxial tests on fully saturated samples were carried out at confining pressures of 140, 280, 420, 560kPa. Duplicate tests were performed at each confining pressure to ensure that consistent results were obtained. A back pressure of 350kPa was employed to saturate the specimens. The samples were then isotropically consolidated for 24 hrs before being sheared at a constant rate of axial strain of 1% per hour. Monitoring and data reduction were made using an ELE Data Acquisition unit (ADU) and a Hewlett Packard computer.

Deviator stress and volume strain versus axial strain curves are shown in Fig. 1. Volume strains are compressive at all confining pressures. The response is somewhat brittle with near linear stress strain curves followed by a clear peak and then strain softening to a residual deviator stress. The volumetric strain is also linear for the first 2–3% of strain, indicating elastic compression of the cemented sand skeleton. This is followed by dilation near failure for the low confining pressure of 140kPa. At larger confining pressures, the tendency for dilation is suppressed and the volume continued to decrease until the peak stress is reached.

To further characterize the influence of cementation, the stress strain response for the cemented sand is compared to that of the same sand tested earlier without cement additive, (Ismael and Ahmad, 1989) in Fig. 2. As shown, cementation leads to a decrease of axial strain to peak and an increase in stiffness. The peak deviator stress also increases and the rate of dilation at failure increases with cementation especially at low confining stresses. Examination of Fig. 2 reveals that the increase of the soil modulus due to cementation is significant. The secant modulus, at 50% of the maximum stress difference,

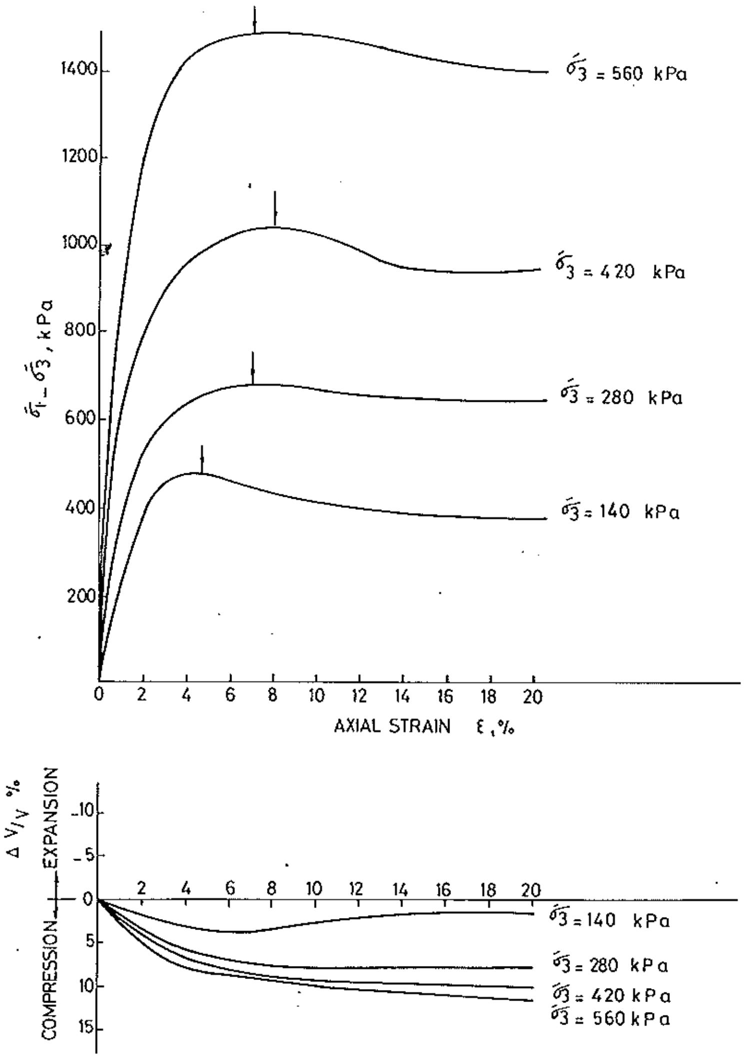

Fig. 1 Stress strain curves for artificially cemented calcareous sand with 1% cement.

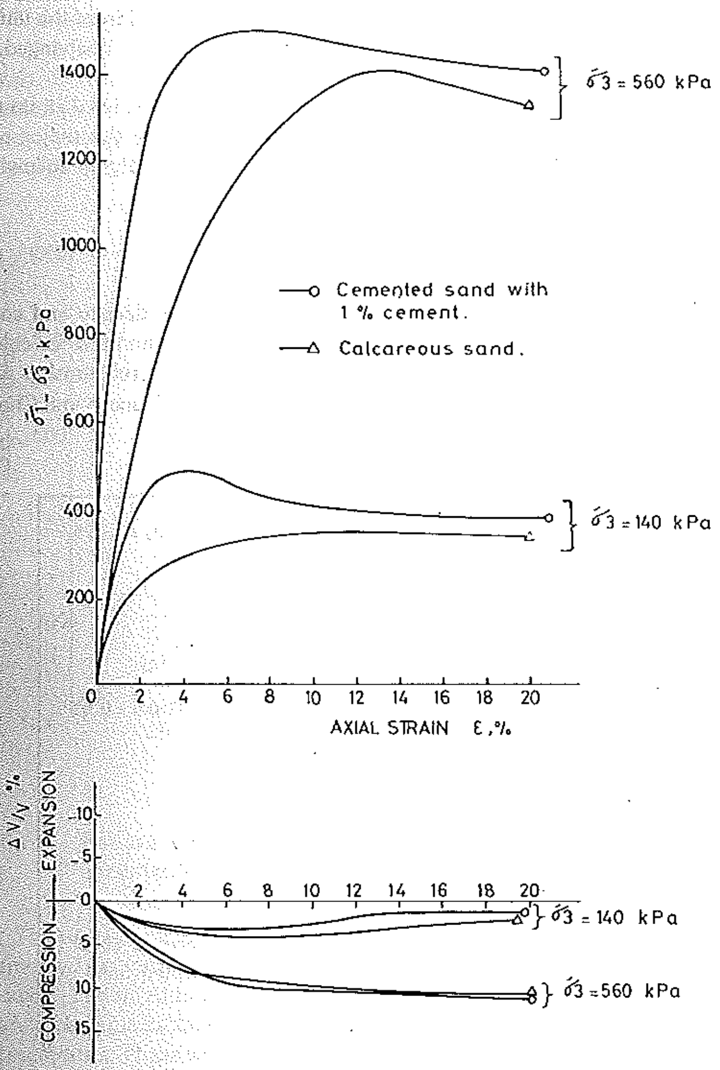

Fig. 2 Comparison of the stress-strain curves for cemented and uncemented sands.

increased by two to four times, while Poissons ratio as obtained from the initial slope of volumetric strain versus axial strain curves, is relatively unchanged.

The initial tangent modulus E_i determined from $(\bar{\sigma}'_1-\bar{\sigma}_3)$ vs. axial strain (ε) curves is plotted versus σ_3 in Fig. 3, where σ_1 and σ_3 are the major and minor principal stresses respectively. The points fit approximately the following relationships

$$E_i = K(\sigma_3)^n \qquad (1)$$

where K and n are constants which depend on the relative density and compressibility. The values of K, n determined herein are 1750 and 0.5 for calcareous sand and 850 and 0.75 for cemented sand. A similar relationship was adopted in non-linear analysis of stress and strain in soils, by Duncan and Chang (1970).

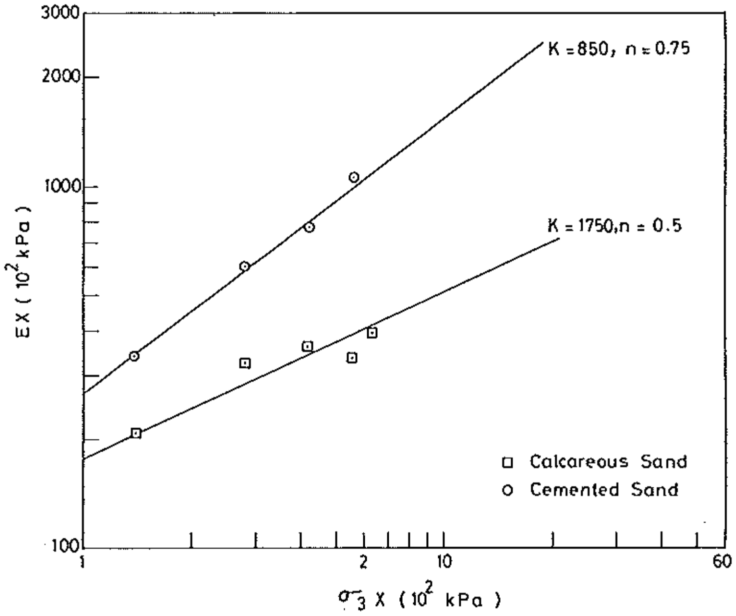

Fig. 3 Initial tangent modulus, E_i vs. confining stress, σ_3.

The peak strength parameters are obtained from a plot of $(\bar{\sigma}_1-\bar{\sigma}_3)/2$ versus $(\bar{\sigma}_1+\bar{\sigma}_3)/2$. This is shown in Fig. 4 for both the cemented and uncemented sands. Both sands have identical angle of friction $\phi = 34°$. However, the cemented sand has a cohesion c of 25kPa compared to zero for the uncemented sand. In terms of the residual parameters, the cemented sand loses its cohesion intercept and maintains the same angle of friction.

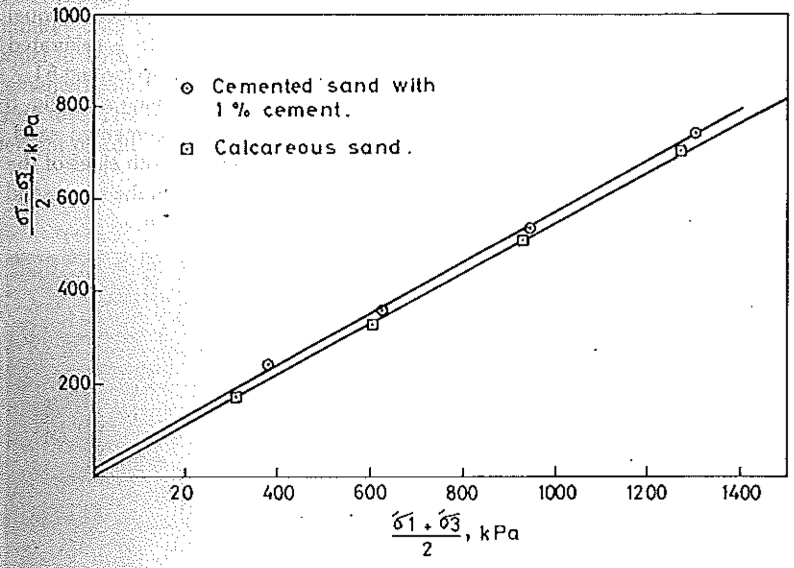

Fig. 4 Failure envelopes and strength parameters for cemented and uncemented calcareous sands.

The preceeding test results have been confirmed by recent tests on artificially cemented carbonate sand from the North West Shelf of Australia, (Allman and Poulos, 1988). Although the sand used is different from the sand employed herein having a carbonate content of 90.7%, it is suitable for comparison with present tests. These workers have found that the peak cohesion increases almost linearly with cement content up to a cement content of 8% which was the maximum employed in their study and that the peak angle of friction remained constant or even decreased with cementation. The stiffness however, as determined by the value of the soil modulus did not increase significantly by cementation compared with the present test results. This is attributed to the high carbonate ($CaCO_3$) content, of the sand employed and the correspondingly high compressibility of the soil matrix.

MODEL FOOTING TESTS

A steel sand box measuring 1 × 1 × 0.5m depth was used in the tests. A rigid frame mounted on the box provided reaction. The loads were applied in equal increments by a manually operated hydraulic jack connected to a calibrated proving ring for measuring the load. A rigid steel rectangular, strip footing 51 × 305 × 51mm thick with a rough base was attached to the proving ring. Fig. 5 shows a general view of the test set-up prior to a test on cemented sand. Displacements were recorded by two dial gauges mounted on both sides of the footing. The same test setup was previously employed in tests on the same sand without the use of a cement additive, (Ismael and Ahmad, 1989).

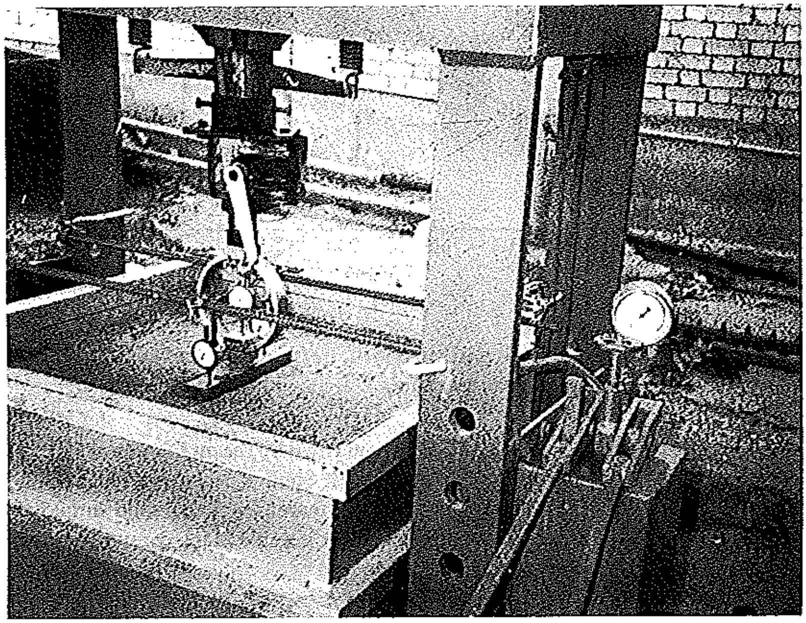

Fig. 5 Test set-up for strip footing on cemented sand.

The tests were carried out by first filling the box with cemented sand having the desired relative density of 66%. Cemented sand was prepared by mixing the sand thoroughly with 1% cement by weight and 10% water. Equal weights of sand were placed, levelled, and tamped to form 76mm layers. Upon completion, the soil in the box was allowed to cure for 28 days. During this period the box surface was covered by wet cloths to allow water absorption. Prior to testing additional water was sprayed for four days to ensure saturation of the cemented sand. Equal increments of stress were applied and maintained for at least 15 minutes until all displacements had ceased. Each loading was approximately equal to 10% of the ultimate pressure. Two identical tests were carried out on cemented sand. In each test density measurements were made using the sand cone test. The overall density was also determined from the weight of the soil cement placed in the box.

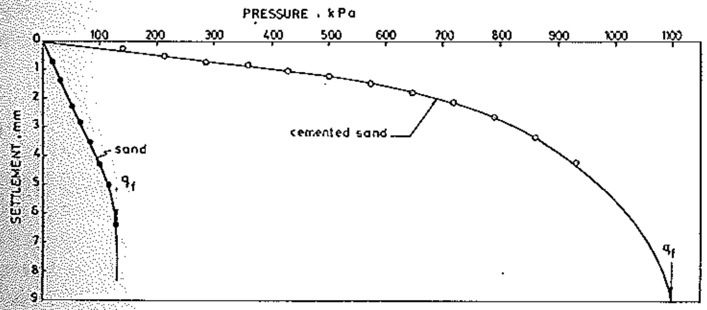

Fig. 6 Pressure-settlement diagrams for strip footings.

ANALYSIS OF TEST RESULTS

Fig. 6 shows the pressure settlement diagrams for the strip footing on cemented sand. For the purpose of comparison the results of tests on the same sand having identical relative density and no cement additive are superimposed. As shown the ultimate bearing capacity of the cemented sand, determined as 1100kPa, is signuficantly larger than the corresponding value of 130kPa for calcareous sand. The ratio being 8.46 appears significantly larger than what might be expected considering that the two soils have identical angle of friction and that the cemented sand has a small cohesion of 25kPa.

For the purpose of interpretation of test results, it is important to note the failure mode of the cemented sand. It has been observed that failure occurred in a brittle manner with vertical displacement mainly below the footing and radial cracks extending in all directions. This is similar to the failure mode of compressible soils, (Vesic, 1973) and soft rocks (Pellegrino 1974). The failure surface in the model tests extended to a distance of 2–2.5 times the width of the footing. The conventional bearing capacity formula for strip footings was applied to the test results as follows:

$$q_f = c\,N_c + q\,N_q + 1/2\;\gamma\,B\,N_y \qquad (2)$$

in which, q_f = the ultimate pressure, q is the surcharge on the sides of the footing, γ is the unit weight of the soil, B is the width of footing and N_c, N_q, and N_γ are dimensionless bearing capacity factors defined as

$$N_q = e^{\pi \tan\phi} \tan^2(\pi/4 + \phi/2) \qquad (3)$$

$$N_c = (N_q - 1) \cot\phi \qquad (4)$$

$$N_\gamma = 2(N_q + 1) \tan\phi \qquad (5)$$

Equation 5 gives the approximate value for N_γ as proposed by Vesic (1975). Another expression for N_γ often used, (Coates, 1981) is:

$$N_\gamma = 1.5(N_q - 1) \tan\phi \qquad (6)$$

The Application of equation 2 to the Model results (although only an approximation) indicates, that since both cemented and uncemented sand have identical angle of friction ϕ = 34° and since both footings reached ultimate failure at nearly the same settlement, the difference in bearing capacity can be attributed to the cohesion of the cemented sand, and the first term of equation 2. The measured difference in ultimate bearing capacity is obtained from Fig.6 as 1100−130 = 970kPa.

For ϕ = 34°, N_c, N_q, and N_γ are calculated from equations 3, 4, and 5 as 42.16, 29.44, 41.06 respectively. Since c = 25kPa, the term cN_c in equation 2 is equal to 25(42.16) = 1054kPa which is comparable to the measured value of 970 kPa.

The preceding analysis indicates that the difference in bearing capacity, and deformation under load of the cemented and uncemented calcareous sand is due principally to the cohesion intercept resulting from cementation. The large difference in bearing capacity shown by these test results is due to the small depth of the model footing and the near absence of side overburden pressure. With this in mind the second and third terms of equation 2 become relatively small compared to the first term. For full size foundations, however, although the bearing capacity will increase with cementation due to the soil cohesion the increase will be relatively modest compared to present test results. This is because the overburden pressure, and the unit weight components will be significantly larger.

This analysis of the bearing capacity of artificially cemented sands may be in applicable if the cement content exceeds some critical value. If such a value is exceeded strong cementation will make the soil behaviour more brittle approaching that of rocks, and theories applicable to rock mechanics may be more suitable. This aspect requires further research and testing to determine at what cement content the soil behavior changes.

PRACTICAL APPLICATIONS

In many instances, naturally cemented sands are encountered at or below the foundation level. It is important not to disturb these soils be over-excavation. Furthermore any laboratory tests to determine the strength and consolidation parameters should be carried out on saturated samples. It has been established, (Ismael et al., 1987) that saturation leads to some reduction of the strength characteristics and increased compressibility of calcareous sands. This is due to loss of some cementation resulting from high temperature and extreme dessication. Some cementing agents are also softened or dissolved by soaking or saturation. The same recommendation is applicable to insitu tests such as the plate load test which should be carried out on presaturated or soaked ground.

Where a thin layer of soft or compressible soil exists below the foundation level, it may be advantageous to replace it with cemented sand having a cement content of 1 to 2%. The results will depend on the geometry and width of foundation, the thickness of the soft deposit replaced, and the properties of the underlying soils. But in general, there will be an increase in the bearing capacity and a significant reduction of settlement under the applied loads. The analysis can be carried out considering the soil as a layered system consisting of a cemented sand layer underlain by the natural ground deposits. It may be possible, if the foundation width is small, to have the stressed zone located entirely in cemented sand. The increase in bearing capacity, and the reduction in settlement, will depend primality on the strength parameter c, and the deformation modulus E of the cemented sand. This increase is proportional to the cement content employed, relative density achieved, and the type and classification of the sand employed.

RECOMMENDATIONS FOR FUTURE WORK

Futher work will be carried out to examine the influence of the cement content on the bearing capacity and settlement of cemented sands. The effect of time on the resulting bearing capacity also needs to be assessed particularly if the soils and groundwater contain significant amounts of sulphates and other salts. It will be extremely beneficial to carry out full scale field tests on actual footings underlain by a layer of cemented sand after curing periods ranging up to five years. From these tests the effect of time can be evaluated, and the scale effects will be eliminated. A better understanding will then be obtained of the effects of replacing soft or loose soils beneath the footings with a compacted soil cement layer. The effect of side overburden pressure should also be examined by footing tests at different depths below ground level.

SUMMARY AND CONCLUSIONS

A program of triaxial compression tests and laboratory model tests on strip footings was carried out on an artificially cemented sand to determine its strength characteristics and bearing capacity. Cement was used as an additive in the amount of 1% to produce weak cementation. Based on test results the following conclusions are reached:

1. The effect of cementation on the peak strength parameters c and ϕ is to cause no change in the angle of friction ϕ, and to introduce a cohesion c = 25kPa.
2. Appropriate strength parameters are obtained from samples which are presaturated prior to shear.
3. Cemented sands are more brittle compared to uncemented sands of the same relative density. The soil modulus is significantly increased due to cementation which led to a stiff response during shear in the triaxial test.
4. The failure mode of a strip footing on artificially cemented sand is in shear with radial cracks and no heave observed on the sides of the footing. The settlements under applied loads are significantly reduced due to cementation.

5. The conventional bearing capacity theory can be applied to weakly cemented sands. However, if the soil is strongly cemented, it will behave in a brittle manner approaching that of soft rocks. Further research is required to study the increase in bearing capacity with cementation and the appropriate theories for behavioral predictions.
6. The results of field loading tests on naturally cemented sands having different degrees of cementation will be extremely beneficial for a comprehensive understanding of the behavior of these soils.

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