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DISCUSSION

The mechanics of cemented carbonate sands

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The Authors have tried to separate the effects of cementation from those of the associated changes in particle size and mineralogy. We have also been studying the behaviour of cemented carbonate sands and the effects of different cement contents and densities on that behaviour (Huang & Airey, 1993). A consequence of this approach has been that differences in mineralogy and grading occur between different mixes, and tests to investigate the effects of these differences have been performed. The observations from these tests, some of which are presented here, provide additional evidence on the effects of grading and mineralogy on the soil response. It appears that the determination of which effects may be ascribed to the cementation and which to other factors is more complex than is indicated by the Authors; nevertheless, the patterns of behaviour and general observations of the Authors agree with data from our tests.

In our study a fine to medium carbonate sand from the North West Shelf of Australia and a gypsum cement have been used. This discussion is concerned primarily with the one-dimensional response of soil–cement mixtures, although some triaxial data are mentioned. Mixtures of sand, cement and various pore fluids were placed in a loose state in a cylinder 55 mm in diameter by 200 mm high, and compressed at a steady rate of 5 mm/min until the samples reached a height of 110 mm. The pore fluid was allowed to drain through porous discs at each end of the sample, and the vertical faces of the cylinder were coated with silicon grease to minimize friction. From the known masses and specific gravities of soil and cement, graphs of void ratio plotted against vertical stress have been determined. For pore fluids other than air the rates were sufficiently slow for the stress–void ratio graphs to be practically rate-independent and the stresses are thus believed to represent effective vertical stresses. Triaxial samples were prepared by one-dimensional compression to predetermined densities and cement contents using a similar procedure to that already described (Huang & Airey, 1991).

The effects of grading on the compressibility of the sand during one-dimensional compression have been studied. The sand was sieved and a fine fraction passing 150 μm and retained on 75 μm (about 37%) and a coarse fraction greater than 625 μm (coarsest 10%) were combined in different proportions. The results of the compression tests on dry mixtures are shown in Fig. 15. As is well known (e.g. Powers, 1968; Youd, 1973), and as reported by the Authors, adding different size particles together results in a reduction of their void ratio. As the mixtures are compressed they appear to approach different normal compression lines with the coarsest material requiring the least load to reach a given density and the finest material the greatest load. At high stresses there is a clear trend between these extremes related to the relative proportions of the fine and coarse fractions. In addition the slope of the compression line varies from lowest for the coarse sample to highest for the finer sample. Also shown in Fig. 15 are the results for the natural sand, and for the natural sand with its grading modified by the addition of an extra 20% of the finer material. The natural soil has mostly fine sand and its compression line, as might be expected, lies between those for the coarse and fine material. The addition of further fine material to the natural grading has no appreciable effect on the compression line for dry samples but moves it slightly to the right

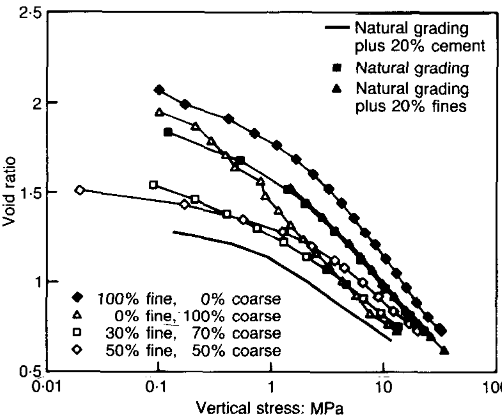

Fig. 15. Effect of grading on the one-dimensional compression response for dry samples

for the water-saturated samples (see Fig. 16), as might have been expected from the preceding results. In this case the addition of fines had only a minor effect on the grading, and had little effect on the initial void ratio. The effects of grading on the compression lines appear to be different from the Authors' results shown in Fig. 1. However, the data suggest that the lines will cross at higher effective stress, and perhaps show the same pattern as is evident in Fig. 15. Previous studies of the effects of grading on the response in one-dimensional compression (e.g. Hardin, 1987) have suggested similar trends to those reported here, but the data have been more confusing than illuminating.

The addition of 20% gypsum fines to the natural sand results, as shown in Fig. 15, in further reductions of the initial void ratio and movement of the compression line to the left. The reduction in initial void ratio can be explained because the gypsum particles are much finer than the soil particles. However, the compression line was expected to shift to the right with the increased fines content—the opposite of what occurred. The same patterns with respect to changes of grading and the addition of gypsum were observed when the samples were compressed with water as the pore fluid (Fig. 16). It is believed that these tests with gypsum were performed sufficiently quickly to minimize the cementation, yet slowly enough to minimize any excess pore pressures. From Fig. 16 it can be seen that the gypsum and soil fines lie at opposite extremes, which suggests that differences in mineralogy, shape and chemistry of the gypsum and soil are also contributory factors. Differences in shape are relatively minor as photomicrographs (Huang & Airey, 1991) have shown the soil and cement to be similarly angular. Differences in the mineralogy affect the specific gravities of the gypsum and the carbonate soil which are 2·39 and 2·82 respectively, and thus even if the void ratios are identical the densities will be different, possibly leading to differences in behaviour. Differences in the physico-chemical behaviour of soil and cement are more difficult to determine, but can be inferred from some of the observations now presented.

Figure 17 compares the effects of different pore fluids on the one-dimensional compression responses for the natural soil with those for the natural soil with 20% gypsum. For the rate of compression used the compression lines move to the right as the pore fluid changes from water to silicon oil (viscosity 20 cS) to air. The responses with oil and water were practically rate-independent; however, the dry samples showed significant rate effects, and with a reduction to a compression rate of 0·05 mm/min the responses of the dry and oil-saturated samples were practically identical. Clearly the pore fluid is influencing the results, but this effect occurs independently of the presence of gypsum. These effects appear to be related to soil fabric as shear box tests (Al-Douri & Poulos, 1992) have shown the frictional properties of this sand to be independent of the pore fluid. The addition of 20% gypsum moves the compression line to the left for each pore fluid. Surprisingly, after the gypsum is allowed to hydrate and form cementation bonds, the compression line shifts to the right of the line for the uncemented soil, as shown in Fig. 18 for the isotropic responses from triaxial compression tests. Similar results are given for both isotropic and one-dimensional compression in Fig. 4. It was

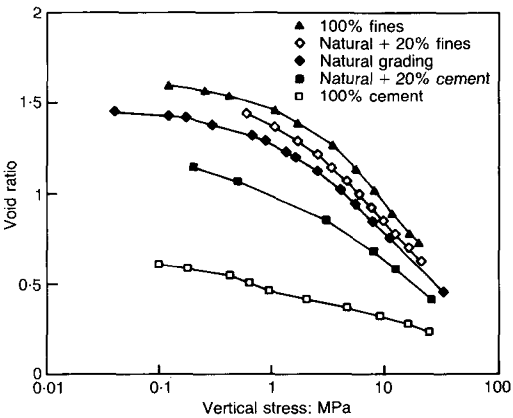

Fig. 16. Effect of soil and gypsum fines on the one-dimensional compression responses for water-saturated samples

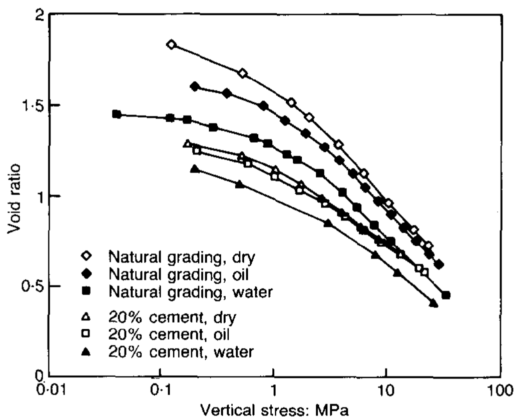

Fig. 17. Effect of pore fluid on the one-dimensional compression responses

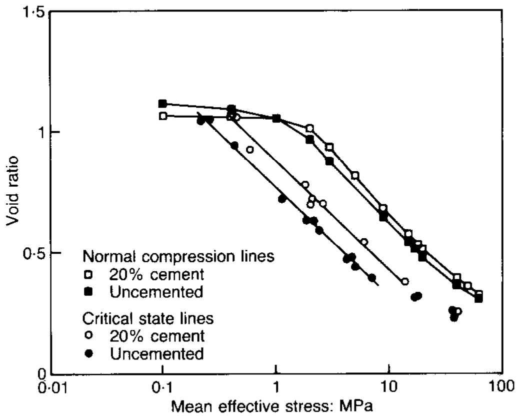

Fig. 18. Isotropic compression and critical state lines

suggested that continued loading beyond yield would cause the soil state to converge with the uncemented destructured soil, but as noted by the Authors, there appears to be little convergence and, as shown in Fig. 18, for stresses up to 60 MPa the compression responses were still essentially parallel. The hydration reaction appears to have caused a permanent shift of the compression lines. The cementation also caused a shift in the critical state line in our tests (Fig. 18). It is generally accepted that the position of the critical state line is very sensitive to small changes in grading, but other factors related to mineralogy and fabric may also be important (e.g. Verdugo, 1992), and indeed might be anticipated in the light of the different effects of adding unhydrated and hydrated gypsum on the normal compression line.

In addition to the compression tests described, some triaxial shear tests were performed on uncemented sand with and without added soil fines of <75 μm (Huang, 1994). The effect of adding the fines was to reduce the peak deviator stress and pore pressures slightly, but the ultimate frictional behaviour was unaffected. In comparison tests on cemented samples isotropically compressed to ten times the yield pressure gave higher deviator stresses and pore pressures than uncemented samples, although again the ultimate frictional behaviour was identical. These results appear to indicate that the cementation has effects in addition to those related to grading changes.

As discussed in the Paper, the movement of the normal and critical state lines as a result of changes in grading, mineralogy and cementation has significant implications for the expected behaviour. The Authors conclude that the effects of grading were more important than the change in mineralogy. These conclusions can be seen to be a consequence of the uniformly graded soil used in their experiments. In the tests we have described the change in grading from adding further fines had relatively little effect on the soil behaviour, and the differences are believed to be largely related to mineralogical and physico-chemical effects. Before hydration adding gypsum moved the normal compression line to the left, whereas after hydration it moved to the right of the uncemented base soil. In view of the fine nature of the particles the change in grading might be expected to move the normal compression line to the right, irrespective of the hydration.

It is suggested that the shift of the normal compression line is permanent after hydration and that this effect has a significant influence on the strength of the soil. The shifts in the normal compression and critical state lines have a major impact on the soil strength, which would increase even if no difference in specific volume were to occur as a result of cementation. It appears that the process of cementation has changed the soil in some way so that the cemented de-structured soil is different from the initial constituents. In that case the appropriate reference de-structured soil which can be used to determine the effects of the cementation, following Leroueil & Vaughan (1990), should also be different from the initial uncemented soil and gypsum mixture.

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Authors' reply

Drs Huang and Airey have studied the influences of particle mineralogy and pore fliuid chemistry on the compression of carbonate soils. Their discussion is based largely on the results of one-dimensional compression tests carried out in a long oedometer and a small number of tests carried out in a triaxial apparatus.

All the work described in the Paper was carried out in triaxial cells. We tested a calcium carbonate sand (Dog's Bay sand) which was either uncemented or artificially cemented with gypsum (calcium sulphate). We found that the grading of the soil had a significant effect on its behaviour and so reference uncemented samples contained unhydrated gypsum in the same quantity as in an equivalent cemented sample so that the gradings were the same. To prevent hydration in uncemented samples the pore fluid, and the fluid in the drainage leads, was silicon oil; silicon oil was also used as the pore fluid in cemented samples after the gypsum had been hydrated in the presence of water.

From the data in Figs 15 and 16 Drs Huang and Airey conclude that the mineralogy of the fines content had a major influence on the compression behaviour because the addition of calcium carbonate fines caused the one-dimensional compression curve to move upwards slightly to higher voids ratios, whereas the addition of gypsum fines caused a substantial downwards movement of the compression curve to lower voids ratios. These data appear to contradict the data given in Figs 1 and 2 which show that the mineralogy of the fines—calcium carbonate or calcium sulphate—had no significant influence on either the compression behaviour or the critical states of the Dog's Bay sand which was tested. The explanation for these different results may lie in the different gradings of the two soils and in the changes to these gradings brought about by the addition of the various fines.

Dog's Bay sand is a poorly graded fine to medium sand with a silt content of only about 1%. It appears that the natural soil used by Drs Huang and Airey was much better graded than the Dog's Bay sand we used.

Gypsum fines pass the 63 μm sieve and in our tests the addition of gypsum plaster increased the fines (< 63 μm) fraction of Dog's Bay sand from 1% to 24%. The flattening of the grading curve by the addition of fines increases the density of soil or decreases the specific volume or voids ratio at a given pressure. As expected, Fig. 1 shows that uncemented Dog's Bay sand with unhydrated gypsum fines has a lower initial specific volume and the normal compression line has a lower intercept N and a smaller gradient λ than has the same soil without the addition of the gypsum fines. When adding calcium carbonate fines to the soil we ensured that these fines also passed the 63 μm sieve so that in both cases material was added to the bottom of the grading curve and the resulting grading curves were the same. The addition of calcium carbonate fines was found to have practically the same influence as the addition of gypsum fines.

On adding gypsum to their soil Drs Huang and Airey have seen the same effect that we observed and, up to this point, the two sets of data are in agreement. It is only in their tests where calcium carbonate fines were added that their data diverge from ours. The calcium carbonate fines which they added appear to be between 75 μm and 150 μm, which is significantly coarser than gypsum. Since their soil is also better graded these fines may not be adding to the bottom of the grading curve like gypsum but to the middle of the curve. This would explain why the addition of these fines had only a small influence on the compression behaviour. We would agree that it is certainly possible that the mineralogy of the fines influences the behaviour of soil but we do not believe that the data which Drs Huang and Airey present show this conclusively, and our own data show no influence at all provided that the gradings are maintained the same.

Drs Huang and Airey also note the importance of the pore fluid on the compression behaviour. In work at the City University on the mechanics of soft carbonate rocks and soils Cuccovillo (1993) tested sand–gypsum mixes with different pore fluids. She also has observed that with water as the pore fluid the normal compression line and the critical state line have lower volume intercepts (N and Γ) than when silicon oil is used as the pore fluid. However, this line of work was not pursued because of uncertainty in the determination of the specific volumes of samples containing oil as the pore fluid. In addition, it was not possible to know accurately how much of the water pore fluid would have been absorbed by the gypsum during hydration, how the hydration might be influenced by confining pressure and what would be the resulting effect on the specific gravity of the material. Nevertheless it is interesting that Drs Huang and Airey have made similar observations for their natural soil. Coop & Lee (1992) have shown that the plastic volumetric strain during compression results largely from particle breakage. It follows therefore that the greater compression with water as the pore fluid must result from particles being weaker in the presence of water than in the presence of silicon oil or when dry.

Drs Huang and Airey have misinterpreted our statement on the post-yield convergence of the states of initially cemented and uncemented samples under compression. We believe that these should converge but that large strains are often required to achieve this. Fig. 18 does not make the correct comparison for checking this convergence because the compression behaviour of the cemented soil should be compared not with that of the natural soil but with a mixture of natural soil and unhydrated gypsum so that the gradings are the same. It should also be noted that when artificially created soils are being tested it is desirable to model real soils. Fig. 19 shows data from Cuccovillo & Coop (1993) in which reconstituted samples of a natural calcarenite were made successfully. Samples of the weakest grade of calcarenite were gently broken under water by hand, avoiding damage to the particles as much as possible. The reconstituted samples were then created by pluviation. A tentative normal compression line is shown in Fig. 19. The isotropic compression lines for reconstituted samples and for intact samples of various grades of natural calcarenite appear to converge with each other and with the normal compression line, but only at very high stresses.

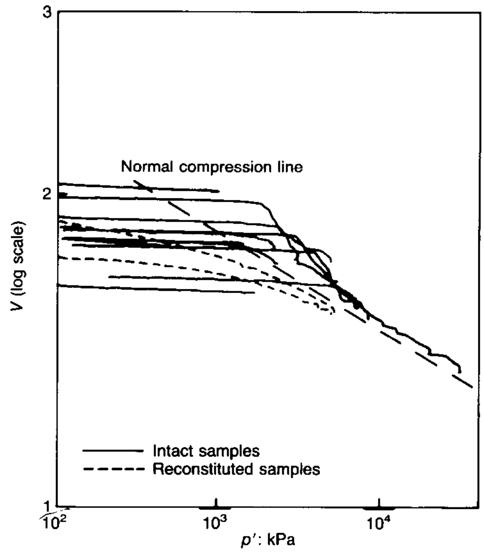

Fig. 19. Isotropic compression of intact and reconstituted samples of a natural calcarenite (after Cuccovillo & Coop, 1993)

Drs Huang and Airey conclude that the reference destructured soil should be different from the initial uncemented soil and gypsum mixture. Their data do not show this conclusively because of the differences in the gradings of their samples with calcium carbonate and gypsum fines. We would agree that in some cases this could be true but it is clearly not the case for the Dog's Bay sand we used. There is no evidence that the mineralogy of the fines had any significant influence on the behaviour of our uncemented soil mixtures. We were careful to use the same pore fluid throughout our test programme and so the data for our cemented and uncemented samples are compatible with each other although different from the behaviour of the same material with water as the pore fluid.

REFERENCES

Al-Douri, R. H. & Poulos, H. G. (1992). Static and cyclic direct shear tests on carbonate sands. *Geotech. Test. J., ASTM* **15,** No. 2, 138–158.

Coop, M. R. & Lee, I. K. (1993). The behaviour of granular soils at elevated stresses. In *Predictive soil mechanics*, pp. 186–198. London: Thomas Telford.

Cuccovillo, T. (1993). *The mechanics of soft rocks.* Research report GE/93/07. London: City University.

Cuccovillo, T. & Coop. M. R. (1993). The influence of bond strength on the mechanics of carbonate soft rock. *Proc. Int. Conf. Hard Soils and Soft Rocks, Athens* **1,** 447–457.

Hardin, B. O. (1987). 1-D strain in normally consolidated cohesionless soils. *J. Geotech. Engng Am. Soc. Civ. Engrs* **113,** No. 12, 1449–1467.

Huang, J. T. (1994). *Effects of cementation and density on cemented soils.* PhD thesis under review, University of Sydney.

Huang, J. T. & Airey, D. W. (1991). The manufacture and index testing of cemented carbonate soils. *Proc. 9th Asian Reg. Conf. Soil Mech., Bangkok* **1,** 143–146.

Huang, J. T. & Airey, D. W. (1993). Effects of cement and density on an artificially cemented sand, *Proc. Int. Conf. Hard Soils and Soft Rocks, Athens* **1,** 553–560.

Leroueil, S. & Vaughan, P. R. (1990). The general and congruent effects of structure in natural soils and weak rocks. *Géotechnique* **42,** No. 4, 655–658.

Powers, T. C. (1968). *The properties of fresh concrete.* New York: Wiley.

Verdugo, R. (1992). Discussion on The critical state of sands, by K. Been *et al. Géotechnique* **42,** No. 4, 655–658.

Youd, T. L. (1973). *Factors controlling maximum and minimum densities of sands.* STP 523. ASTM, 98–112.