Isotropic Compression Behaviour of Fibre Reinforced Cemented Sand

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ABSTRACT

Fibre-reinforced cemented sands have many applications in improving the response of soils. In this paper, an experimental investigation for the analysis of fiber-reinforced cemented sand in the framework of isotropic compression is presented. The experimental investigations were carried out using a high pressure triaxial apparatus having the capacity of 64 MPa of confining pressure. Tests have been conducted on Portaway sand specimens reinforced with randomly oriented discrete polypropylene fibers with different percentages of fiber and cement contents. Results are presented in the form of e-logp` curves as well as SEM (Scanning Electron Microscopy) micrographs. The effects of the addition of fibre in sand and cemented sand for different initial void ratios were investigated. The results demonstrate that the influence of fibre is not significant in both cemented and uncemented sand during the isotropic compression stage. Moreover, from the SEM micrographs it could be seen that there is breakage of sand particles and cement bonds. The fiber threads were seen pinched and found rarely broken in the specimen exhumed after isotropic compression.

Key Words: **High-Pressure, Cemented Sand, Isotropic Compression, Triaxial Compression, Fibre, Cement.**

1. INTRODUCTION

The compression behaviour of geomaterials has always been a topic of investigation in geotechnical engineering, because many field problems are analysed solely based on soil properties obtained from compression tests [1]. For example, the great majority of settlement calculations for geotechnical structures are made based on the coefficient of compressibility of the soil layers beneath the foundations [2]. Recent research demonstrated the potential engineering applications in the reinforcement of soil layers to be used as base for spread foundations e.g. [3-5] increasing bearing pressures and giving a noticeably stiffer response than that carried out on the non-reinforced soil. These research mainly focussed on the separate effects of fibres and cement on sand behaviour, including during isotropic loading e.g. [6-8], there has not yet been a study of their comparative effects or their combined effects in isotropic loading except a few for instance, [7,9].

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Furthermore, it has been reported in the literature e.g. [10-12], that sand under isotropic loading is relatively incompressible at low stresses, and large volume changes only occur at very high stress levels, where, presumably particle crushing becomes dominant mechanism of volume change. A complete description of the volumetric behaviour of a sandy material requires testing to high stress levels usually much higher than usually encountered in typical engineering structures. Therefore, the behaviour of fibre reinforced cemented sand under isotropic compression at high pressures in exploring the effectiveness of fibre and/or cement on compression characteristics and particle crushing would be significant. However, to model a framework for reinforced materials, the microscopic changes due to macromechanical forces are significant to incorporate. For this purpose SEM analysis is often used by many researchers e.g., [13-16]. Thus coupling the macro and micro mechanics would give a broader portrait of the micromechanical behaviour of the materials. Therefore, the focus of this paper is to investigate the isotropic compression behaviour of fibre reinforced cemented sand and to compare and validate the results with reported work on fibre reinforced cemented sand. Validation of results using micromechanical analysis is also focussed in this paper.

2. TESTING EQUIPMENTS

2.1 High Pressure Triaxial Apparatus

A high pressure testing system, developed at the University of Nottingham, United Kingdom in conjunction with GDS (Global digital systems) Instruments Ltd. was used. A schematic diagram of the testing system is shown in Fig. 1.As shown in Fig. 1, displacement (or load) in the high-pressure system was applied from the bottom of a loading frame via a displacement controller. A 100kN submersible load cell was used to measure the vertical load at the top of specimen. The cell pressure was applied through a GDS DPVC (Digital Pressure/Volume Controller). Another DPVC was used to control the backpressure from the top of the specimen and measure the volumetric change in a drained test, or to control the volumetric change and measure the pore water pressure in an undrained test. The DPVCs used in this study had a capacity of 64 MPa. A high capacity pressure transducer was also used to measure the pore water pressure at the bottom of the specimen. Further detail of the testing system can be seen in [17].

2.2 Scanning Electron Microscope

The SEM analyses were carried out using EDAX Quanta 600 scanning electron microscope as shown in Fig. 2. An SEM is essentially a high magnification microscope, which uses a focussed scanned electron beam to produce images of the sample, both top-down and, with the necessary sample preparation, cross-sections.

3. MATERIAL TESTED

Well-graded, medium quartz sand from Sheffield (England), so-called Portaway sand was used as the base material for the cemented specimens. The index properties of Portaway sand, determined by British Standard methods [18], are given in Table 1. The sand grains were mainly sub angular and sub rounded in shape. Before the preparation of cemented specimens, the sand was passed through 2mm sieve to remove gravel size particles and washed through 0.063 mm sieve under the running water to remove fines before subsequent specimen's preparation. Portland cement and Polypropylene fibres were used as reinforcing materials.

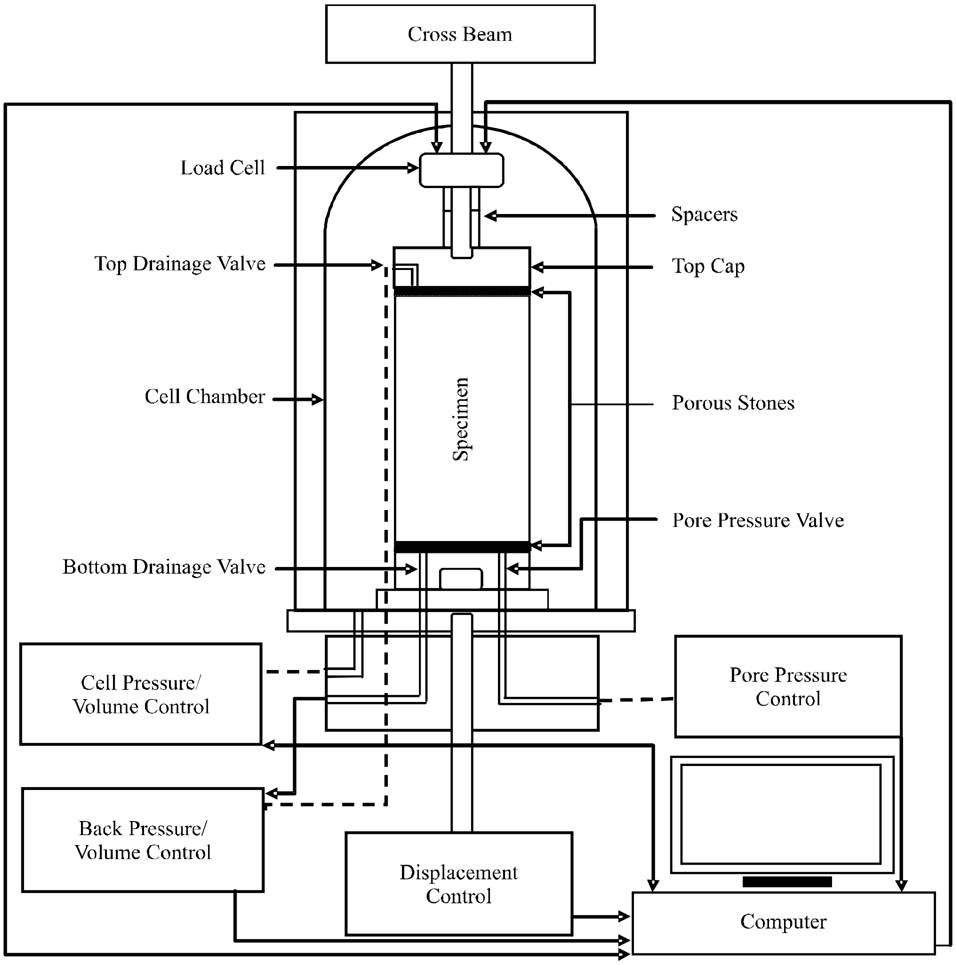


FIG. 1. SCHEMATIC DIAGRAM OF HIGH-PRESSURE TRIAXIAL TESTING SYSTEM

(a) OUTSIDE VIEW

(b) INSIDE VIEW

FIG. 2. SCANNING ELECTRON MICROSCOPE

Polypropylene fibres are synthetic fibres made from Polypropylene. The physical properties of polypropylene fibres are given in Table 2. Ordinary Portland cement was used as a cementing material, having consistent strength meeting all the conformity criteria in [19]. The OPC has its initial setting time 80-200 minutes and the specific gravity of 3.15.

4. SPECIMEN PREPARATION AND TESTING PROCEDURES

The cemented specimens (50 mm diameter 100 mm height) were prepared by initially mixing relevant amounts of dry Portaway sand and 2 and 5% ordinary Portland cement by weight of dry sand. Mixing of dry materials was continued until a uniform appearance of the sand-cement mixture was obtained. Water was then added to the mixture in accordance with the optimum moisture content of 10% and further mixing was performed until a homogeneous appearance of the moist sand-cement mixture was achieved. The mixture was then stored in an airtight container to avoid any moisture loss before subsequent compaction.

TABLE 1. INDEX PROPERTIES OF PORTAWAY SAND

Properties	Values
Effective grain size D10: mm	0.19
D30: mm	0.29
Mean grain size D50: mm	0.39
D60: mm	0.42
Uniformity Coefficient D60/D10	2.21
Specific Gravity, G_s	2.65
e_{max}	0.79
e_{min}	0.46

TABLE 2. PHYSICAL PROPERTIES OF POLYPROPYLENE FIBRES

Properties	Values
Length, mm	22
Diameter, mm	0.023
Tensile Strength, N/mm^2	0.95-1.3
Notched Impact Strength, kj/m^2	3.0-30
Softening Temperature	80°C
Density, g/cm^3	0.905

Fibre reinforced cemented specimens were prepared by hand mixing sand, cement, and polypropylene fibres. Water was added to sand prior to adding fibres to achieve uniform mixing. The mixing was carried out until a homogenous mixture was achieved.

The specimens were compacted in three layers into a 50mm diameter and 100mm high split mould to a targeted maximum dry unit weight of 17.4 kN/m^3. To achieve a greater uniformity of specimens the undercompaction method, proposed by [20] was used. After compaction, the specimens were allowed to cure inside the mould for 24 hours. The moulds were then dismantled and the specimens were stored in a humid room to cure for 14 days before testing.

5. RESULTS AND DISCUSSION

High-pressure isotropic compression tests were carried out on samples of sand, fibre reinforced sand, cemented sand, and fibre-reinforced cemented sand. The effects of different initial void ratios and cement/fibre contents on the compression characteristics of Portaway sand were investigated. Before and after isotropic compression, the specimens were investigated for subsequent deformations and changes in the composite due to compression. The list of typical isotropic compression tests discussed is given in Table 3. The effects of high confining pressure on particle crushing, fibres breakage and cement bond breakage were examined further with the help of SEM.

5.1 Effect of Initial Void Ratio

The stress paths during isotropic compression may be plotted on a graph of specific volume, v versus logarithm of mean effective stress, ln (p'). It is well established that for soils compressed for the first time, there is a unique relationship between specific volume and mean normal effective stress p', which is represented by a straight line on the graph of λ against ln (p'), known as the isotropic NCL (Normal Compression Line) represented by Equation (1).

$$v = l + e = N + \lambda ln(p') \qquad (1)$$

Where, v is the specific volume, e is the void ratio, λ is the compression index, p' is the average mean effective stress and N is the specific volume at unit mean effective stress.

From the compression curves of fibre reinforced uncemented sand as shown in Fig. 3, it can be noticed that by the progressive increase in the confining pressure there is a tendency for convergence of the compression curves of the specimens prepared at different initial void ratios. At the end of isotropic compression, the curves tend to approach to a unique void ratio at high pressures shown as dashed line. Consoli, et. al. [7] also reported similar observations for fibre reinforced sand. The values of λ and N obtained from NCL are 0.160 and 1.9 respectively. Dos, et. al. [10] also reported similar value for the slope of NCL but N value is quite low as compare to the reported values of 3.09.

TABLE 3. SUMMARY OF TYPICAL ISOTROPIC COMPRESSION TESTS

Test (MPa)	C (%)	F (%)	D_r (%)	e_0	e_c
0F0C20	0	0	90	0.495	0.383
0.25F0C20	0	0.25	90	0.495	0.364
0.5F0C20	0	0.5	90	0.495	0.363
0.5F5C20	5	0.5	80	0.529	0.449
0.5F0C50	0	0.5	89	0.495	0.272
0.5F0C50	0	0.5	48	0.687	0.341
0.5F5C50	5	0.5	86	0.523	0.364
0.5F5C50	5	0.5	62	0.584	0.464
0.5F5C50	5	0.5	40	0.657	0.453

Where, in 0.25F5C50MPa, 0.25F shows the per cent of fibre, 5C shows per cent content of cement 50MPa is the effective confining pressure.

Similarly, from Fig. 4, which shows the e-ln (p') curves of fibre reinforced cemented sand, it can be observed that the cemented sand also demonstrates similar trend of convergence in the compression curves having a tendency to approach a unique void ratio at high pressures as is noticed for fibre reinforced uncemented sand. This suggests that by the increase in confining pressure during isotropic compression, there is tendency of convergence in the compression curves for both fibre reinforced uncemented and cemented sands, which are prepared at different initial void ratios. The only difference that can be noticed in the compression curves is the difference in the compression path and the compression index. For instance, at the end of compression the final void ratio for

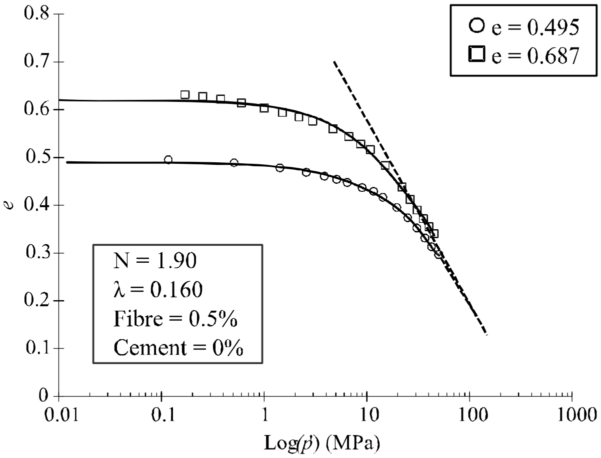


FIG. 3. ISOTROPIC COMPRESSION CURVES OF FIBRE REINFORCED SAND AT DIFFERENT INITIAL VOID RATIOS

fibre reinforced uncemented sand is less than the final void ratio for fibre reinforced cemented sand, which suggests that fibre reinforced cemented sand, is relatively less compressible as compared to the fibre, reinforced uncemented sand. The numerical values N and λ obtained for fibre reinforced cemented sands are 2.03 and 0.173 respectively. There is a direct significance of N and λ for the analysis of isotropic compression.

5.2 Effect of Fibre in Sand and Cemented Sand

The effect of the addition of 0.25 and 0.5% fibre in sand at constant void ratio is shown in Fig. 5. It can be seen that the addition of fibre has little or no effect on the compression curve e-ln (p') of sand and they follow the same compression line up to 2MPa. After this fibre reinforced sand samples tend to compress marginally more. During isotropic compression, the fibres are compressed in all directions, and therefore do not function as tensile reinforcement as in triaxial shear test upon shearing large lateral tensile strain occurs in the soil. There are contradictory results reported in literature about fibre contribution in isotropic compression behaviour for instance, Ling, et. al. [21] pointed out that under isotropic compression reinforcement may not play any role in the initial phase of loading. Michalowski, et. al. [22] also reported that fibres in compression do not contribute to reinforcement, and may even have an adverse effect. Whereas, Ibraim, et. al. [23] reported that the presence of reinforcement provides an extra resistance to the compaction, causing a less dense packing as the quantity of fibres is increased. This can result in more volumetric compression of fibre reinforced sand. It can also be seen that 0.25 and 0.5% fibre reinforced samples have the same compression throughout the test, which in turn suggest that varying fibre content has also no effect in isotropic compression. Fibre reinforced sand samples apparently seem to have more compression than sand. This might be due the slight variation in the initial void ratio and also may be due to the fact that fibres have a specific gravity, Gs, of 0.9 which results in lesser initial void ratio. As compression is achieved by interparticle slip and rotation, fibre could provide a smooth surface which facilitates more compact rearrangement of particle. This results in slightly higher compression. The e-ln (p') curves of fibre reinforced cemented and cemented Portaway sand are shown in Fig. 6. It can be seen that both the cemented and fibre

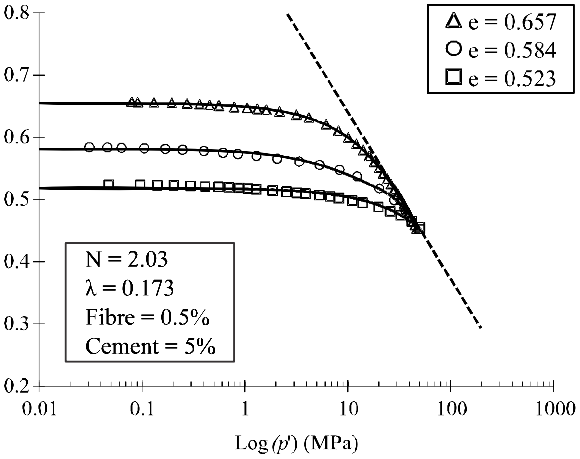


FIG. 4. ISOTROPIC COMPRESSION CURVES OF FIBRE REINFORCED CEMENTED SAND AT DIFFERENT INITIAL VOID RATIOS

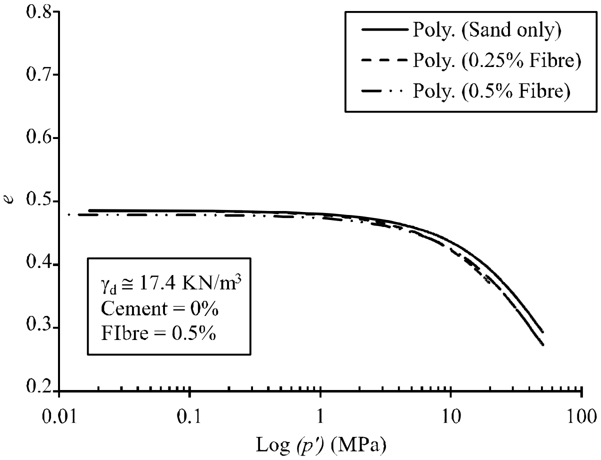


FIG. 5. EFFECT OF FIBRE CONTENT ON e-ln (p') CURVES OF PORTAWAY SAND PREPARED AT CONSTANT INITIAL VOID RATIO

reinforced cemented samples follow nearly the same line of compression. It can also be seen that similar to the effect observed in fibre reinforced sand, the fibre reinforced cemented sample compresses more at higher pressures above 8MPa.

5.3 SEM ANALYSIS

5.3.1 Fibre Distributions

To investigate the mixing, distribution and homogeneity of fibres microscopically in cemented and uncemented samples, SEM analysis was carried out on samples before and after isotropic testing. Fig. 7 shows SEM micrograph of fibre reinforced cemented and uncemented soil samples before testing showing distribution of fibres in sand and cemented sand. It is important to note that SEM micrographs represent the qualitative information regarding the distribution as investigation is always limited to very small area and to a specific horizontal or to plane of failure. The distribution of fibres which looks reasonably uniform and consistent at macroscale may not have the same level of uniformity and consistency at micro level as shown in Fig. 7. It is also worth mentioning that SEM micrograph shown is of about a 1-2mm diameter part of the whole sample surface. In the fibre reinforced cemented sample taken at a magnification of 50x shown in Fig. 7(a), the sample was analysed before isotropic compression and shows only the top surface of the specimen. There can be seen consistent bonding of the grains in their natural bedding plane, some poor bonding and cement deposition on the surface of the sand grains and fibres can also be seen as well. Fig. 7(b) which is taken at a magnification of 100x shows the SEM micrograph of fibre reinforced uncemented sample. It can be seen that fibres are distributed somehow uniformly and making a network of fibre with sand grains. Similar distribution has also been shown by Tang et al. [24].

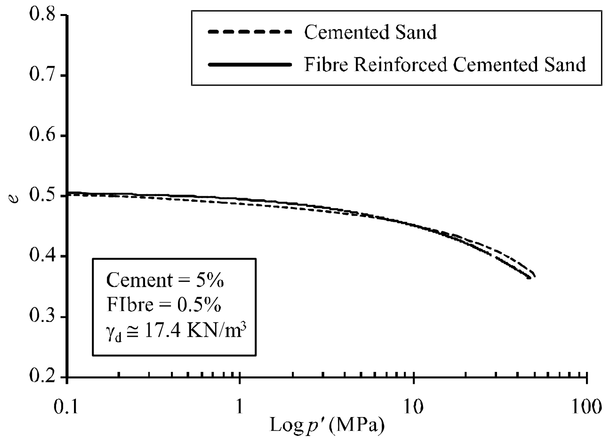
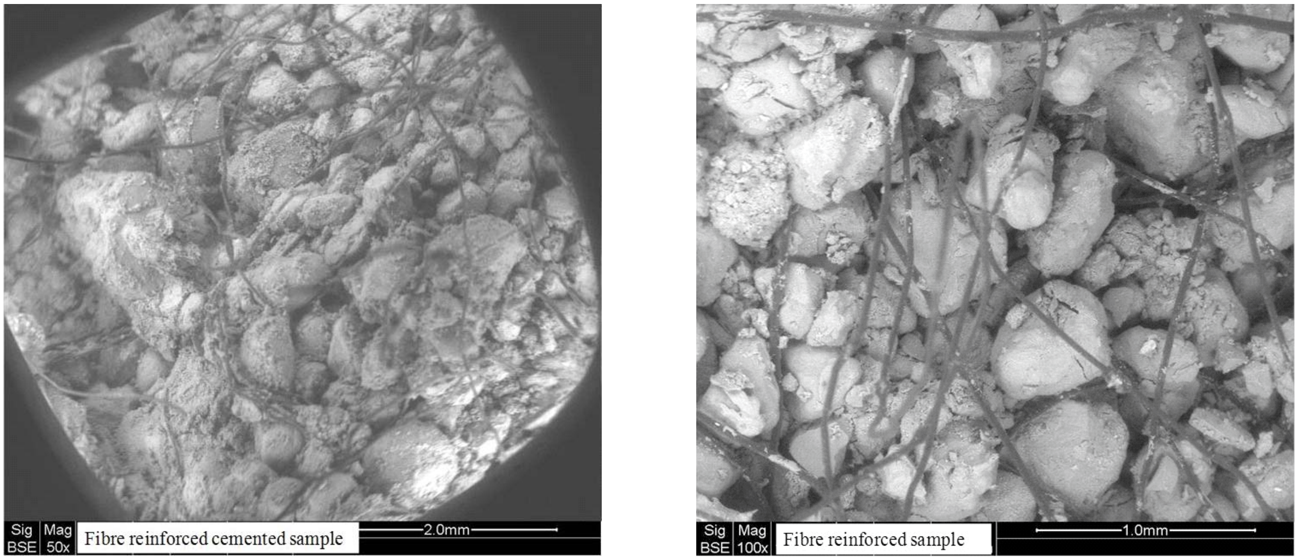


FIG. 6. EFFECT OF FIBRE ON e-ln (P') CURVES OF CEMENTED SAND PREPARED AT CONSTANT INITIAL VOID RATIO

5.3.2 Particle Crushing and Fibre Breakage

In order to investigate the effect of isotropic compression on fibre reinforced cemented and uncemented sand, the isotropically compressed specimens to a confining pressure of 50MPa were further investigated with the help of the SEM microscope. For this purpose, both cemented and uncemented samples were taken.

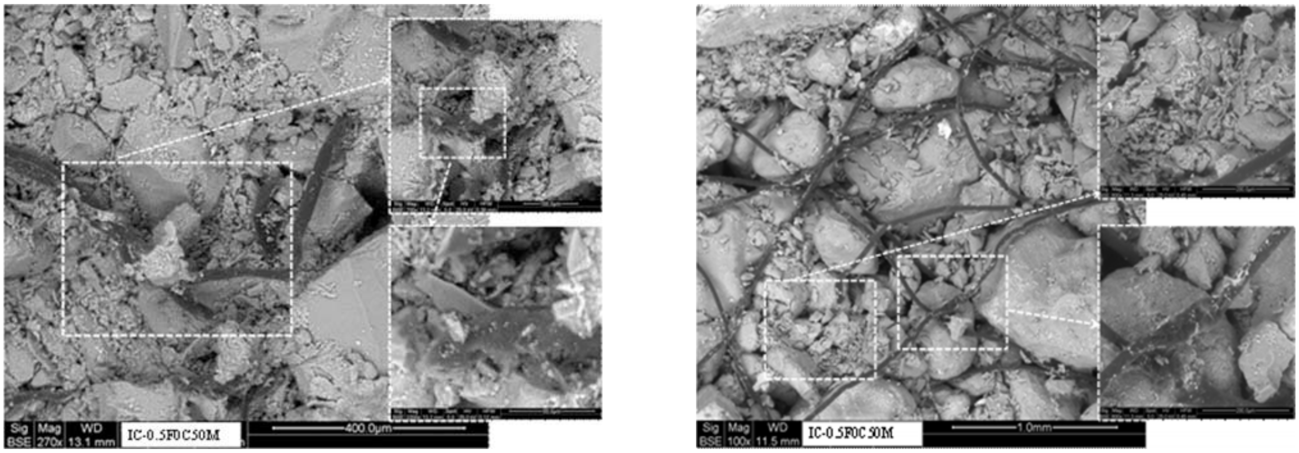
The results of isotropic compression tests carried out on cemented and uncemented sand samples during isotropic compression have shown negligible effect of fibres as discussed previously. SEM micrographs taken at magnifications ranging from 100-2000x shown in Fig. 8 also reveals that there is little effect of isotropic compression in terms of fibre breakage, however, fibre elongation. Pinching and twisting is noticeable. It can be seen that particle crushing is very significant and readily noticeable while fibres are seen distorted in shape but are not seen broken suggesting they were not subjected to tensile stresses.



(a) 0.5% FIBRE AND 5% CEMENTED REINFORCED SAMPLE

(b) 0.5% FIBRE REINFORCED SAMPLE

FIG. 7. FIBRE REINFORCED SAMPLES SHOWING DISTRIBUTION OF FIBRE BEFORE TESTING



(a) SHOWING PINCHING AND TWISTING OF FIBRES

(b) PARTICLE CRUSHING AND TWISTING

FIG. 8. SEM MICROGRAPH OF 0.5% FIBRE REINFORCED SAMPLE ANALYSED AFTER ISOTROPIC COMPRESSION SHOWING

6. CONCLUSIONS

This paper was aimed at a fundamental understanding of the behaviour of fibre reinforced cemented and uncemented sand under isotropic compression. High pressure isotropic compression tests were carried out on samples of uncemented and cemented Portaway sand at different initial void ratios, different fibre and cement contents.

From the experimental investigations, it was observed that the effect of initial void ratio for both cemented and uncemented fibre reinforced sands appear to diminish at high pressures and there is convergence in the isotropic compression curves. Similar to uncemented sand, the cemented sands with different initial void ratios converge towards a unique final void ratio by the progressive increase in the confining pressure. Therefore, the variation of initial void ratio has less significance at high confining pressures.

Keeping the initial void ratio constant the effect of the addition of fibre in sand and cemented sand was also examined and it could be seen that the effect of fibre is either very nearly negligible or the addition of fibre increases the overall compression of both sand and cemented sand.

The value of λ and N for sand and fibre reinforced sand is 0.160 and 1.88 respectively while for cemented and for fibre reinforced cemented sand the values are 0.173 and 2.03.

Regarding the particle crushing and fibre breakage, fibre/cement content was not found to resist the deformation due to higher confining pressures. For instance, for both uncemented and cemented fibre reinforced sand, SEM micrographs indicated significant particle crushing, fibre twisting and punching. However, for fibre reinforced sand, only fibre twisting and pinching was seen and there was hardly any fibre breakage. This verifies the results seen in e-ln (p') curves that fibres did not contribute in resisting the isotropic compression due to only being subjected to compressive stresses.

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