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Technical Note

Mechanical characteristics of soft clay treated with fibre and cement

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ABSTRACT: In this study, the influence of three types of fibre – polypropylene, recycled carpet and steel – on the mechanical properties of cement-treated clay is investigated. Cement-treated clay specimens were prepared with cement contents of 5%, 10% and 15% by weight of dry soil, and cured for 14 days. To investigate and understand the influence of different fibre types and contents, three different percentages of fibre content were adopted. The results of unconfined compression tests on 90 cylindrical samples of cement-treated clay with varied cement and fibre contents are analysed to discern the relationships between these parameters and the key mechanical properties, including unconfined compressive strength and stiffness of treated soil. Furthermore, indirect tension test results of a further 90 treated soil samples have been used to determine the influence of fibre and cement content on the tensile strength of the treated soil. The fibre reinforcement increases the peak compressive strength. The addition of fibres increases the residual strength and changes the brittle behaviour of the cement-treated clay to that of a more ductile material. The tensile strength of the cement-treated clay is increased by adding carpet and steel fibres, but small quantities of polypropylene fibres do not influence the tensile strength.

KEYWORDS: Geosynthetics, Polypropylene fibre, Carpet fibre, Steel fibres, Cement-treated clay, Tensile strength, Unconfined compressive strength

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1. INTRODUCTION

When the soil encountered at a particular site is not suitable for construction, design engineers have various options. They can bypass the poor soil, replace it with superior soil, redesign the structure for the poor condition, or improve the soil's properties by, for example, mixing it with materials such as cement, lime, gypsum, fly ash, milled slag or other cementitious by-products. Cement stabilisation techniques, including jet grouting and deep cement mixing (dry and wet), have been used worldwide, especially in South East Asia and North America and recently in Australia, for stability and deformation control of land reclamation and road construction projects, and in deep excavations in soft clay. Deep soil mixing (DSM) is an in situ soil improvement approach that mixes in situ soil with strengthening agents, usually cementitious, through hollow, rotating shafts with cutting tools, mixing paddles and/or augers mounted at various locations along the shafts. The compressibility of the soil is similarly altered, with the cement-treated soil having much higher preconsolidation pressure than the untreated soil. Exceeding preconsolidation pressure, due to heavy structural loads, leads to a sharp decrease in the void ratio and deformation (Uddin *et al.* 1997; Balasubramaniam *et al.* 1998; Topolnicki 2004), which has also been observed in natural soils (Burland 1990; Lapierre *et al.* 1990; Nagaraj *et al.* 1998; Liu and Carter 1999). However, there have been efforts by several researchers (e.g. Fatahi *et al.* 2011) to introduce innovative methods to reduce the cement usage in DSM projects, minimising the carbon footprint and cost.

On the other hand, in order to solve the environmental problems generated by waste production, different solutions are presented. One of these solutions is to produce synthetic fibres specifically engineered as an additive to enhance material performance. In addition, according to Freedonia Group (2011), the processed or clean waste associated with the large production rate of carpet is estimated to be around 7%, amounting to \$4.5 billion worth of goods that are currently destined for landfill sites or incinerators. However, as reported by Miraftab and Lickfold (2008), growing public concern for the environment and tighter restrictions on and costs of landfill sites in recent years have forced many waste producers to look for innovative uses of the waste products in the form of fibres to enhance the performance of various materials.

Although a substantial amount of research has been carried out on sandy or clayey soils reinforced with waste fibres, there is a lack of study on the effect of recycled fibres such as carpet fibres on cement-treated clays, which may be utilised in DSM. In addition, previous studies did not present a comprehensive comparison of the effectiveness of various fibres in improving the strength and stiffness of cement-treated clay (e.g. Maher and Ho 1993; Omine *et al.* 1996; Prabakar and Sridhar 2002; Michalowski and Cermak 2003; Miraftab and Lickfold 2008). If the mechanical characteristics of cement-treated soils can be improved by introducing waste fibres, then two goals can be achieved simultaneously: the cement content required to achieve the required material properties can be reduced, and the use of waste materials helps deal with the emerging issues of our already teeming landfills. In this study, following a brief review of current literature on the application of fibres in geotechnical engineering, the effects of three target fibres (polypropylene, recycled carpet and steel) on the mechanical properties of cement-improved kaolinite clay are investigated, based on unconfined compression and indirect tension test results.

2. FIBRE-REINFORCED SOIL

According to Mandal and Murti (1989), by mixing soil with high-tensile-strength fibres, the engineering properties of the resulting fibre-reinforced soil may be improved. Many years ago, materials such as wood, reeds and rice straw were blended with soil to improve its engineering properties (Xu *et al.* 2004). With the development of synthetic fibres, the application of these materials has grown in soil reinforcement. Some studies dealing with the reinforcement of uncemented and cemented soils using fibre inclusions have been reported (e.g. Maher and Ho 1993; Omine *et al.* 1996; Prabakar and Sridhar 2002; Michalowski and Cermak 2003; Cai *et al.* 2005; Miraftab and Lickfold 2008; Lovisa *et al.* 2010; Liu *et al.* 2011). Polypropylene fibre is a thermoplastic and hydrophobic material with long polymer structure, consisting of carbon and hydrogen atoms. Jiang *et al.* (2010) reported the effects of discrete polypropylene fibres on the engineering properties of soil. The unconfined compressive strength, cohesion and internal friction angle of polypropylene-fibre-reinforced soil showed an initial increase, followed by a decrease with further increase of fibre content. The optimum polypropylene fibre content was determined to be 0.3% by weight of the unreinforced soil. Consoli *et al.* (2003) employed polypropylene fibres with different lengths and diameters at various fibre contents to reinforce sandy soil. It was concluded that the deviatoric stress of the reinforced soil specimens increased with an increase in the fibre length, the fibre aspect ratio and the fibre content, and it decreased with an increase in the fibre diameter alone. Investigations by Sahin (2009) and Chaosheng *et al.* (2006) showed that the most significant effect, which increased with the polypropylene content, was on ductility, with soils of a higher polypropylene content failing at a far greater strain. Miller and Rifai (2004), based on their test results, indicated that polypropylene fibre inclusion reduced the crack formation and hydraulic conductivity of a compacted clay soil.

Once a carpet is out of style, soiled or worn out, it is often thrown away. Approximately half a million tonnes per annum of waste, arising from the disposal of carpets, currently goes to landfill. In the UK alone, 400 000 tonnes of carpet waste is buried in landfills each year. There are established recycling options for a small proportion of this: carpet tiles are recycled by separating the nylon fibres from the bitumen backing; mixed synthetic carpet is shredded, and mixed with rubber crumb and sand to form a surface for equestrian ménages; carpet fibres are pulled, and blended with other fibres to produce products such as underlay and insulation (www.carpetrecyclinguk.com). Reinforcement application is one of the methods for reusing these recycled wastes. Wang (1999) reported benefits of the use of carpet fibres for soil reinforcement, and concluded that the confined compressive strength and residual strength of the soil increase. Field tests showed that shredded carpet waste fibres up to 70 mm long can be mixed into soil with standard equipment. According to Miraftab and Lickfold (2008), nylon carpet pile waste can be successfully mixed with substandard soil up to a maximum of 10%, while enhancing the cohesion and strength of the soil as well as its internal friction.

Steel fibres are used mostly in concrete, and are available in several shapes and sizes that enhance the mechanical properties of the concrete in a broad range. The addition of steel fibres changes the workability of the concrete (Tadepalli *et al.* 2009). Steel fibres are used straight, crimped, hooked single, hooked collated and twisted. It has been clearly demonstrated that hooked steel fibres perform better than straight or crimped fibres (Bayasi and Soroushiah 1992). Mixing steel fibres into lightweight concrete can further enhance its tensile properties (Campione and Mendola 2004; Chen and Liu 2005).

The clay sample used for testing was Q38 kaolinite clay, with an average liquid limit of 50% and plastic limit of 29%. Q38 kaolinite clay is a dry-milled kaolin China clay, of a white-cream colour. Kaolinite is one of the most abundant minerals in soil, and as such is often encountered in in situ conditions. Kaolinite is formed by the breakdown of feldspar, which is induced by water and carbon dioxide, and is often formed by the alteration of aluminium silicate minerals in a warm and humid environment (Murray 1999; Craig 2000). The admixture used in stabilising the experimental clay samples was Portland cement Type I, which is one of the most widely used construction materials in Australia, and is representative of a typical cement type used in DSM construction within Australia. This general-purpose cement complies with the Type GP requirements specified in Australian Standard AS 3972-2010, with 60–150 min of minimum setting time and a soundness of less than 3 mm. In the design of soil–cement mixes, the cement content is the fundamental variable to be adjusted when considering the required strength of the composite mixture. Higher cement contents generally result in increased strength, durability and permeability characteristics. The exact cement content is dependent on the site requirements, as well as on the type of soil being stabilised. Soils of differing compositions react differently to cementitious additives, and therefore designs are specific to in situ conditions. Cement contents of 10%, 15% and 20% of the dry weight of the clay were adopted for the kaolinite samples, and a water content of 150% of the clay liquid limit –parameters similar to those adopted by Lorenzo and Bergado (2004). The above-selected cement content is in good agreement with the typical cement used in mixing conditions for wet deep mixing on-land application reported by Topolnicki (2004).

Table 1. Summary of mixes used in this study

Mix no.	Cement content (%)	Fibre type	Fibre content (%)
1	10	–	–
2		Polypropylene	0.1
3			0.2
4			0.5
5		Recycled carpet	0.5
6			0.75
7			1
8		Steel	5
9			7.5
10			10
11	15	–	–
12		Polypropylene	0.1
13			0.2
14			0.5
15		Recycled carpet	0.5
16			0.75
17			1
18		Steel	5
19			7.5
20			10
21	20	–	–
22		Polypropylene	0.1
23			0.2
24			0.5
25		Recycled carpet	0.5
26			0.75
27			1
28		Steel	5
29			7.5
30			10

For this study, the polypropylene fibres in quantities of 0.1%, 0.2% and 0.5%, carpet fibres in quantities of 0.5%, 0.75% and 1%, and steel fibres in quantities of 5%, 7.5% and 10% were used to reinforce the 10%, 15% and 20% cement-stabilised clay. This producing 81 samples (three samples per mix) for the unconfined compressive test and 54 samples (two samples per mix) for the Brazilian tension test. In addition there were nine control samples without fibre reinforcement. This gave a total of 45 samples per fibre type. The quantities of fibre and cement were expressed as a percentage of the dry weight of the kaolinite clay. Table 1 summarises the mixes used in this study. The polypropylene fibres used in this research are 18 mm Sika monofilament fibres with nominal diameter 22μm, density 0.91g/ml, and Young's modulus 3.5 GPa. Monofilament polypropylene fibre was used rather than fibrillated fibre to prevent any clustering or tangling during the mix, allowing for a more homogeneous mix. Larger fibre content (e.g. more than 0.5% polypropylene fibre) in the mixture results in low workability, and prevents homogeneous mixing. The various fibre contents were selected after considering investigations published in the literature, and the workability of the mixes in the laboratory. The carpet fibres are from polypropylene tufted carpets granulated at 10 mm size in the UK. They came from edge trims from the carpet-manufacturing process, and were then granulated by one of the machine suppliers such as Cumberland using a 10 mm screen. The steel fibres employed in this study have dimensions of 0.4 mm × 0.3 mm × 18.4 mm, and their tensile strength is approximately 1050 MPa. Figure 1 shows the various fibres used in this study.

3. EXPERIMENTAL PROCEDURE

The clay and fibres were initially mixed thoroughly with the water to obtain reasonable workability. For kaolinite, a water content of 75%, which is 50% more than the liquid limit of the soil, was required to produce a mix of adequate workability. Cement slurry with a water-to-cement ratio of 1 to 1 was then added to the remoulded reinforced clay as the stabilising admixture. Alternate hand and mechanical mixing were used to ensure a homogeneous mix for all samples. The resulting mixtures were of reasonable workability for placement into the moulds, which were 100 mm in diameter and 200 mm high; in accordance with AS 5101.4-2008. In order to minimise entrapped air and provide compaction, the mixture was placed in the mould in several layers, and worked into it with palette knives. At this point, the moulds were placed on a vibration table to ensure that entrapped air was minimised, and that the samples were uniform. Plastic cling film sheets were then wrapped round the specimens

(a) (b) (c)

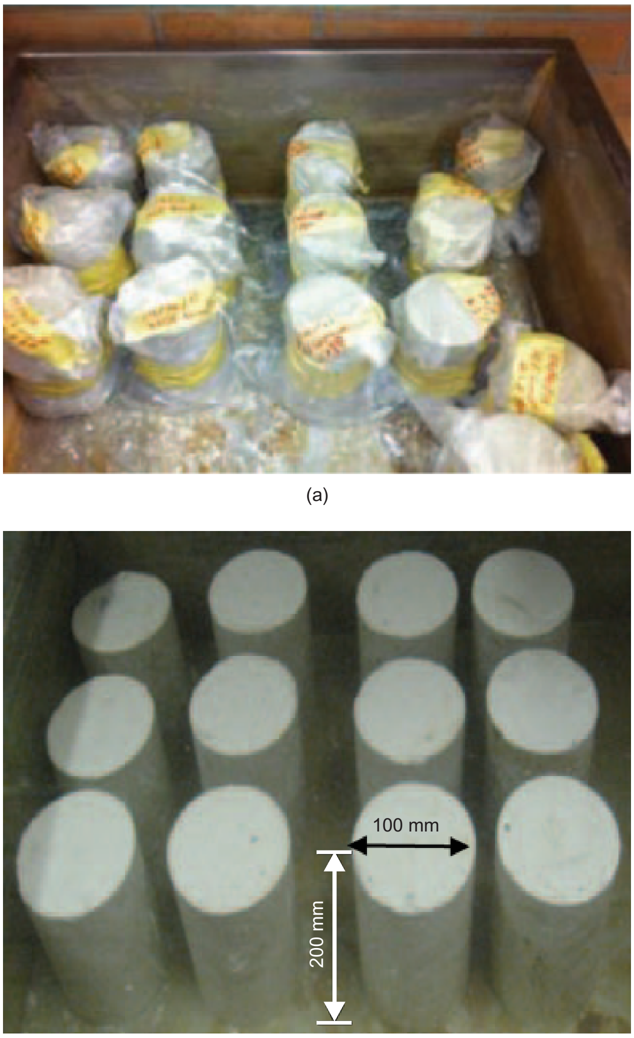
Figure 1. The three types of fibre used in the study: (a) monofilament polypropylene; (b) recycled carpet; (c) steel

to minimise moisture loss, and assist the cement hydration process. The specimens were left to cure in within the moulds and plastic wrapping for 7 days in a controlled ambient environment at 25°C prior to de-moulding. They were then immediately placed to cure in a water bath, where they remained for a further 7 days. Thus the total curing time for the samples was 14 days. After removal from the curing bath, the samples were weighed, and their dimensions were measured. Figure 2 shows the samples curing before testing.

3.1. Unconfined compression test

The compression testing was conducted in accordance with AS 5101.4-2008 (Method 4: Unconfined compressive strength of compacted materials), as well as the relevant literature detailing experimental procedures for testing soil-cement columns (e.g. Lorenzo and Bergado 2004; Liu *et al.* 2008). The specimens were capped with gypsum in preparation for compressive testing in accordance with AS 5101.4-2008, to ensure an even surface for the application of load. The standard specifies that the compressive machine used should comply with the requirements for Grade B of AS 2193-2006, referring to the upper block of the machine having a spherical seat. The machine was set at a load rate of 1 mm/min, and this was kept consistent for all specimens tested. An S-type load cell was used as a transducer to converting the force into an electrical signal, readable on the load cells display. A data logger was used to transfer the data to a readable output. An LVDT displacement transducer was set up against the bearing block of the machine to measure the vertical displacement of the specimen under the applied load. The LVDT readings were used to calculate the strain of the specimens. The axial stress at failure or the unconfined compressive strength of the specimen (σ_f or UCS) is then calculated using

$$\sigma_f = \text{UCS} = \frac{4Q}{\pi D^2} \tag{1}$$



(a)

(b)

Figure 2. Curing of cement- and fibre-treated soil samples before testing: (a) hydration in sealed condition for 7 days, followed by (b) saturation in water bath for 7 days

3.2. Indirect tension (Brazilian) test

The indirect tensile strength was measured in accordance with AS 1012.10-2000, as well as the relevant literature detailing experimental procedures for testing of rock samples (e.g. Yu *et al.* 2006). After measuring the diameter and length of the specimen, hardboard bearing strips were aligned between the top and bottom platen, and the specimen was centred over the lower platen. The load was increased continuously until no further increase in force could be sustained, and the maximum force applied to the specimen, as indicated by the testing machine, was recorded. The tensile strength of the specimen, σ_t, is then calculated using

$$\sigma_T = a\left(\frac{2P}{\pi DL}\right) \tag{2}$$

where P is the maximum load applied; D is the diameter of the sample; L is the thickness of the sample; and a is a shape parameter, which can be estimated as $a = 0.2621k + 1$, in which k is the ratio of the sample thickness to its diameter, as recommended by Yu *et al.* (2006). Figure 3 shows the samples and the set-up used for the unconfined compressive and tensile strength tests.

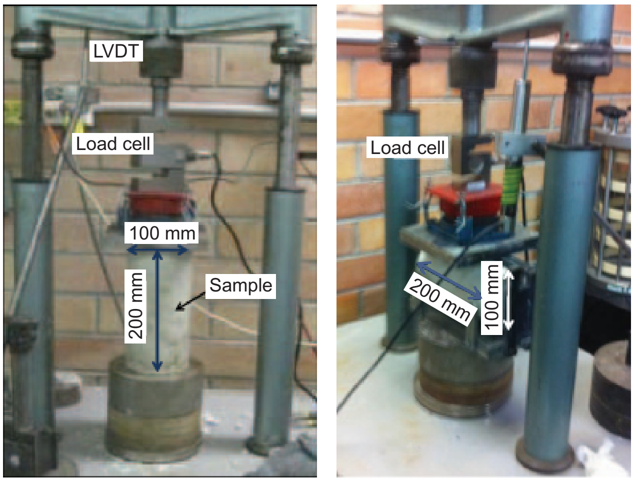
4. RESULTS AND DISCUSSION

Figure 4 shows a selection of stress–strain curves from the unconfined compression tests. Because of the large number of tests in this study, only selected test results indicating the variations of stress–strain curves with fibre type and content are presented.

It is readily observed from Figure 4 that the overall behaviour of the cement-treated soil is significantly influenced by the fibre type and content. The peak strength, stiffness and brittleness are altered. The general pattern that can be observed is the addition of fibres increases the shear strength, and changes the brittle behaviour of cement-treated kaolinite to a more ductile behaviour. The introduction of polypropylene and steel fibres increases the initial Young's modulus of the cement-treated clay, whereas the addition of carpet fibres reduces it.

In order to validate the reliability of the test results, the coefficients of variation (CoV) for the unconfined compressive strength and indirect tensile strength were calculated for every triplicate test. The results indicate that the they range from 2% to 12% for the unconfined compressive strength, and from 5% to 18% for the indirect tensile strength, and that most of them are less than 10%. Thus the distribution of the test results is of low variance, which makes the results from the triple test reliable. Hence, in this study, the average of three measured or calculated results was used for the later analysis.

As anticipated, increases in the cement content resulted in increased strength. As shown in Figure 5, the analysis revealed a varying degree of strength gains with increasing fibre reinforcement content. The polypropylene-reinforced samples showed a clear trend of increasing strength with increasing fibre content. Although the unconfined compressive strength of carpet and steel reinforced samples also increased, the change was less pronounced than for the polypropylene fibres. For example, the addition of 0.5% (polypropylene), 1% (carpet) and 10% (steel fibres)



(a) (b)

Figure 3. Test rigs: (a) unconfined compression test; (b) Brazilian test (indirect tensile strength)

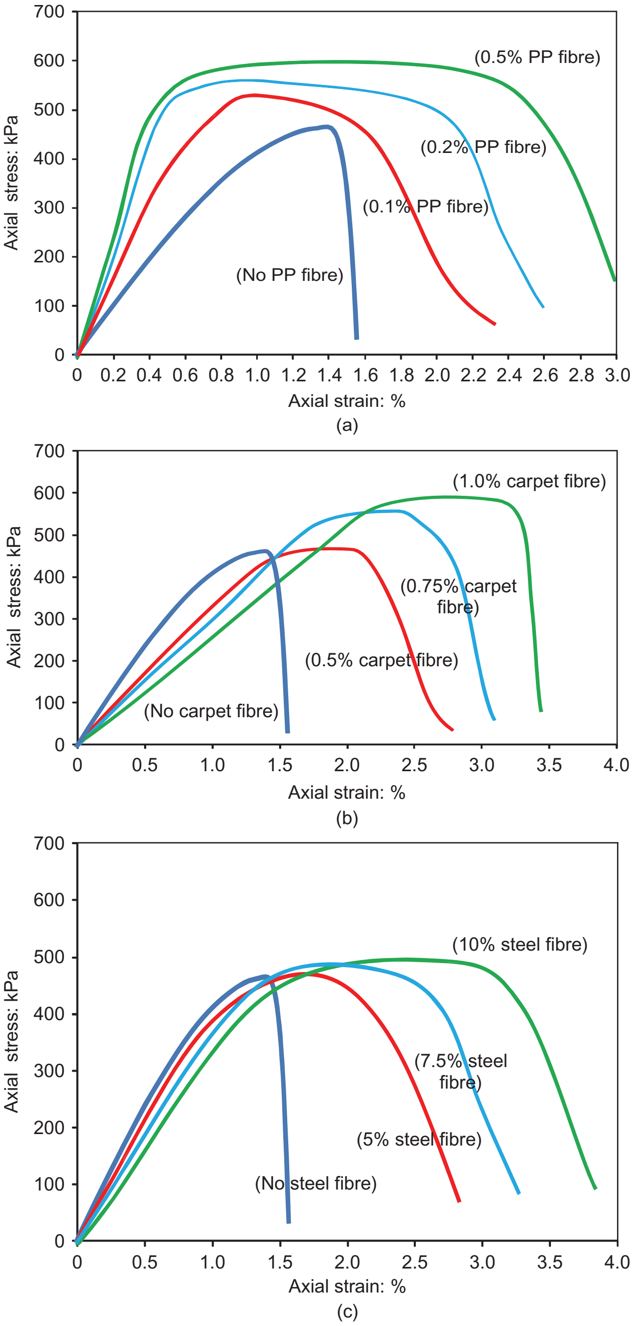


Figure 4. Stress–strain response of clay treated with 20% cement, reinforced with: (a) polypropylene fibres; (b) carpet fibres; (c) steel fibres

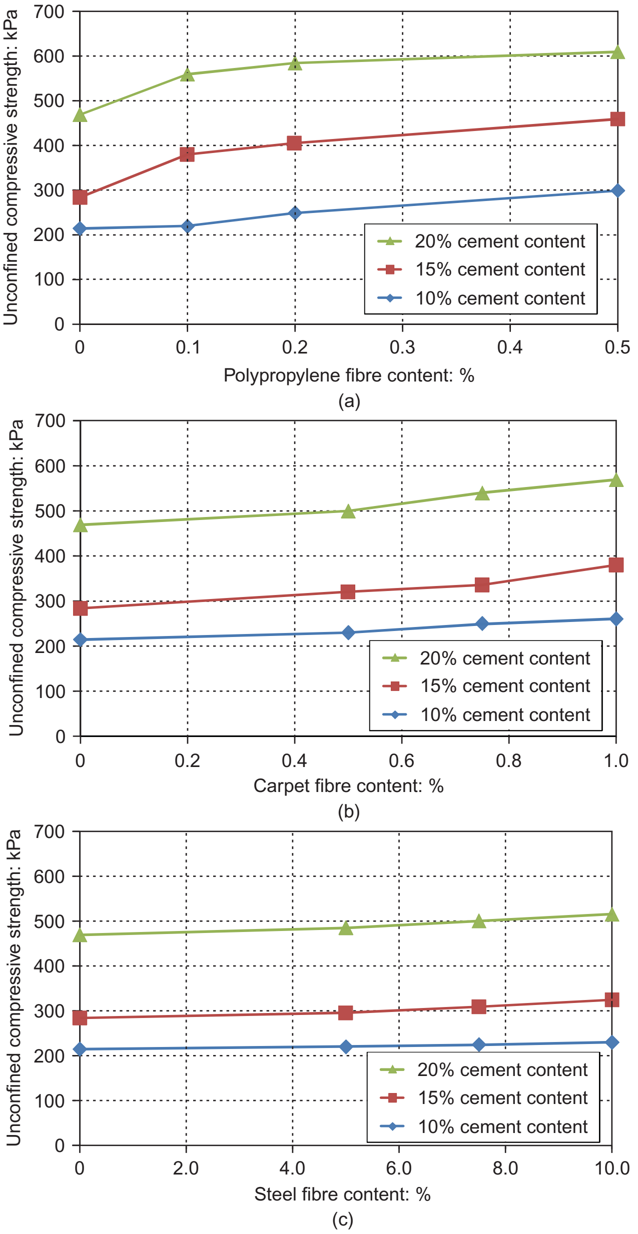


Figure 5. Variation of unconfined compressive strength of kaolinite–cement mixture with: (a) polypropylene fibre; (b) carpet fibre; (c) steel fibre

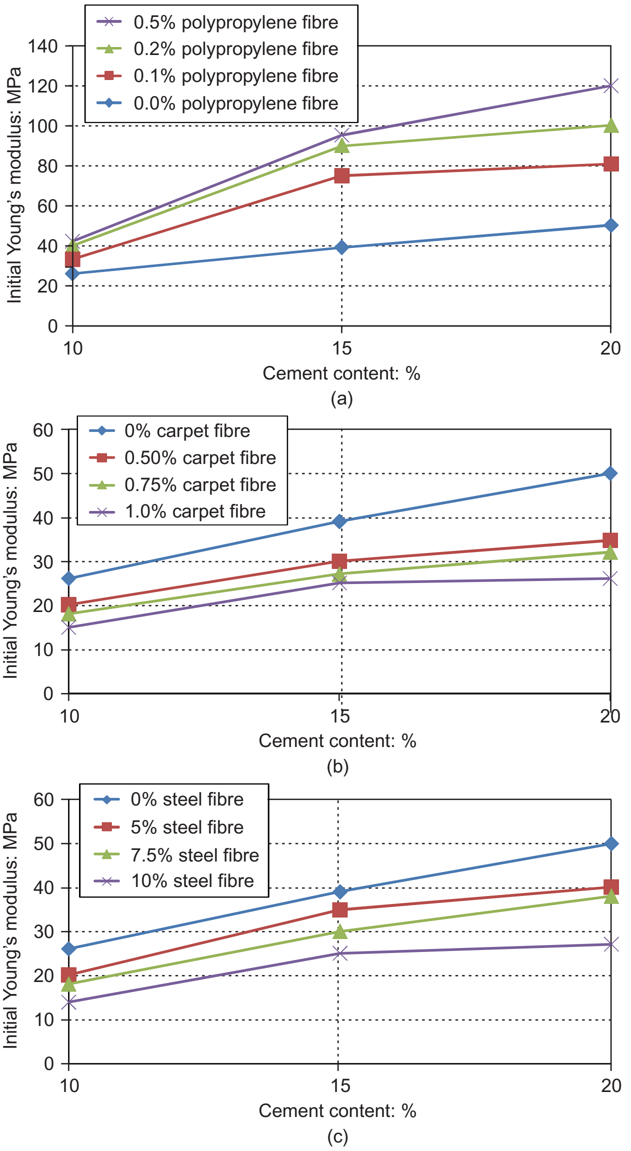


Figure 6. Variation of initial Young's modulus of kaolinite–cement mixture with: (a) polypropylene fibre; (b) carpet fibre; (c) steel fibre

increased the unconfined compressive strength by 25%, 20% and 10%, respectively, in clay samples treated with 20% cement.

Figure 6 shows the relationship between the initial Young's modulus, the fibre content and the cement content. The initial Young's modulus is calculated as the slope of the initial section of the stress–strain curve. As expected, the stiffness of the treated soil increases with the cement content. The samples reinforced with polypropylene fibres show an increase in stiffness with increasing fibre content. Figure 6a clearly shows that, regardless of the percentage of cement used, adding polypropylene fibres increases the initial Young's modulus of the samples. This improvement is more noticeable when the cement content is greater than 15%. However, the stiffness of the cement-treated clay reinforced with carpet and steel fibres decreases with increasing fibre content, as shown in Figures 6b and 6c. This may be as a result of introducing a material that is more plastic than the cement-treated clay, and possibly does not engage very well with the surrounding matrix.

Figure 7 shows the variation of the ratio of E_i (the initial Young's modulus of the sample) to E_f (the Young's modulus at failure) with fibre content and cement content. Figures 7a and 7c show that E_i/E_f increases with increasing polypropylene and steel fibre contents, and reduces with increasing cement content. This suggests that the higher contents of polypropylene and steel fibres increase the ductility of the material, whereas the increased cement content results in reduced ductility. However, as shown in Figure 7b, E_i/E_f decreases with increasing carpet fibre content. According to Figure 7, E_i/E_f ranges between 1.4 and 2.6 for polypropylene fibres, between 1.2 and 1.8 for carpet fibres, and between 1.4 and 2.1 for steel fibres,

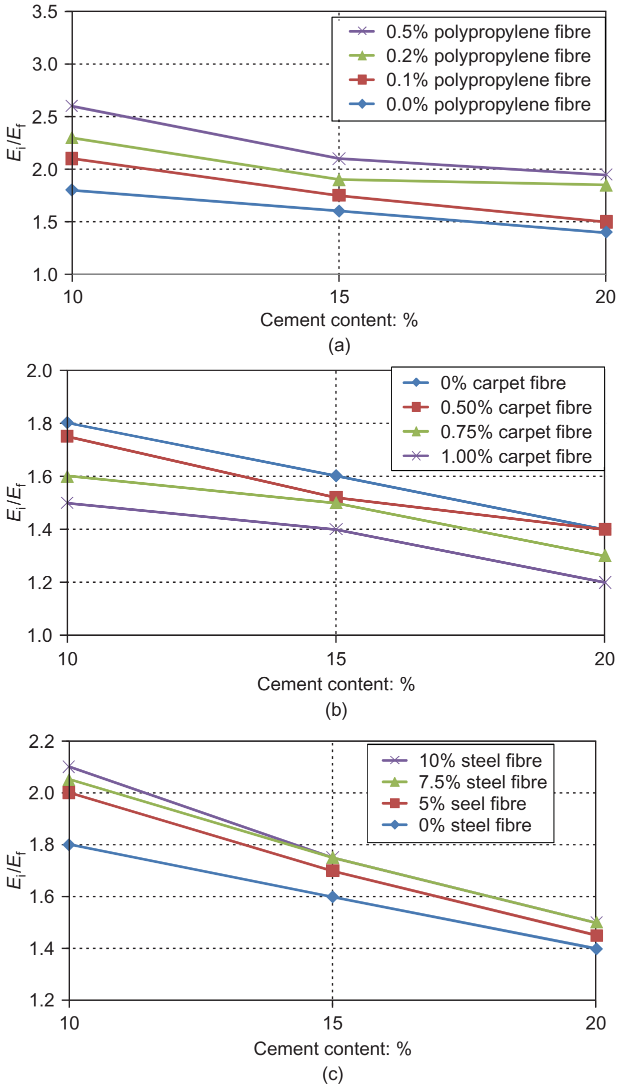


Figure 7. Variation of $E_{\mathrm{i}}/E_{\mathrm{f}}$ of kaolinite–cement mixture with: (a) polypropylene fibre; (b) carpet fibre; (c) steel fibre

within the previously mentioned cement and fibre content ranges. The Young's modulus at failure, E_{f}, is calculated from

$$E_{\mathrm{f}} = \frac{\mathrm{UCS}}{\varepsilon_{\mathrm{f}}} E_f = \frac{UCS}{\varepsilon_f} \tag{3}$$

where ε_{f} is the axial strain at the failure point.

Figure 8 shows the estimated values of the ratio $E_{50\%}$/UCS for the soil samples with various fibre and cement contents, where $E_{50\%}$ is the Young's modulus of the sample at 50% failure stress. The results show that $E_{50\%}$/UCS varies between 70 and 145, 40 and 95, and 40 and 110 for polypropylene-, carpet- and steel-fibre-reinforced treated soil, respectively. The results also show that, regardless of the type of fibre, $E_{50\%}$/UCS shows a non-linear relationship with cement content. The Young's modulus at 50% failure stress is calculated using the formula

$$E_{50\%} = \frac{0.5\mathrm{UCS}}{\varepsilon_{50\%}} \tag{4}$$

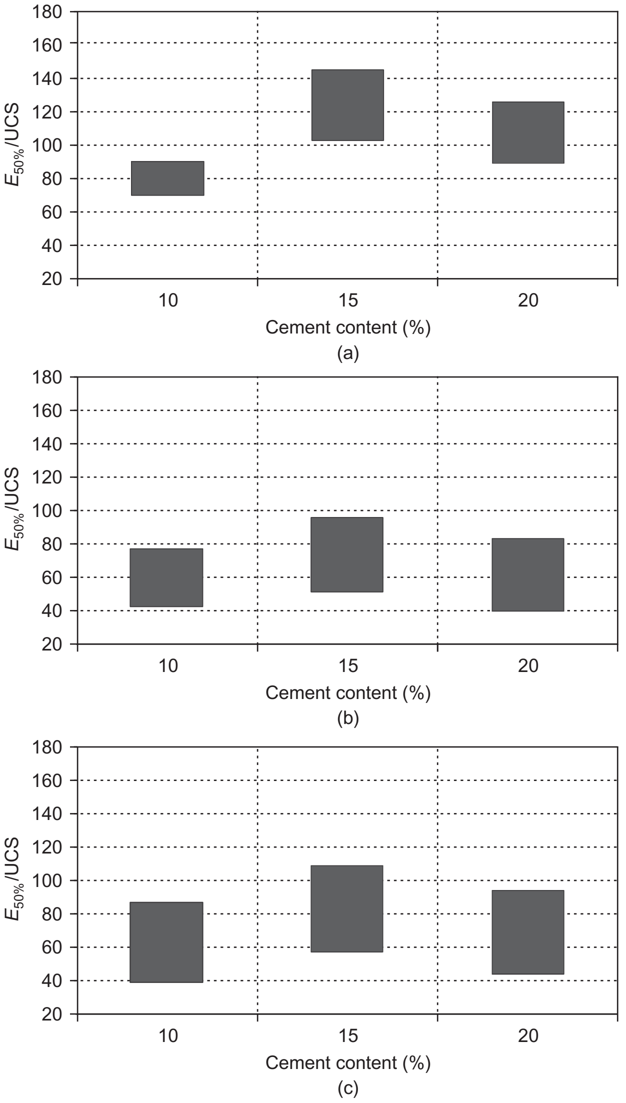


Figure 8. Variation of $E_{50\%}$/UCS of kaolinite–cement mixture with: (a) polypropylene fibre; (b) carpet fibre; (c) steel fibre

where $\varepsilon_{50\%}$ is the axial strain when the normal stress is equal to 0.5UCS.

To investigate the influence of fibre reinforcement on the ductility/brittleness of the treated soil, a brittleness index I_{B} has been adopted, defined by the expression (Consoli *et al.* 1998)

$$I_{\mathrm{B}} = \frac{\sigma_{\mathrm{f}}}{\sigma_{\mathrm{r}}} - 1 \tag{5}$$

where σ_{f} is the axial stress at failure and σ_{r} is the axial stress. Figure 9 shows that I_{B} increases with increasing cement content, and decreases with increasing fibre content. Clearly, the addition of fibres changes the material behaviour to a more ductile one, and hence influences the post-failure behaviour of the cement-treated clay. Of the three fibre types, the addition of carpet fibres has the least influence on the brittleness of the cement-treated kaolinite. This may be because the carpet fibres are shorter than the other two fibre types: thus they can be pulled out of the soil matrix more easily, and at lower strain levels. In

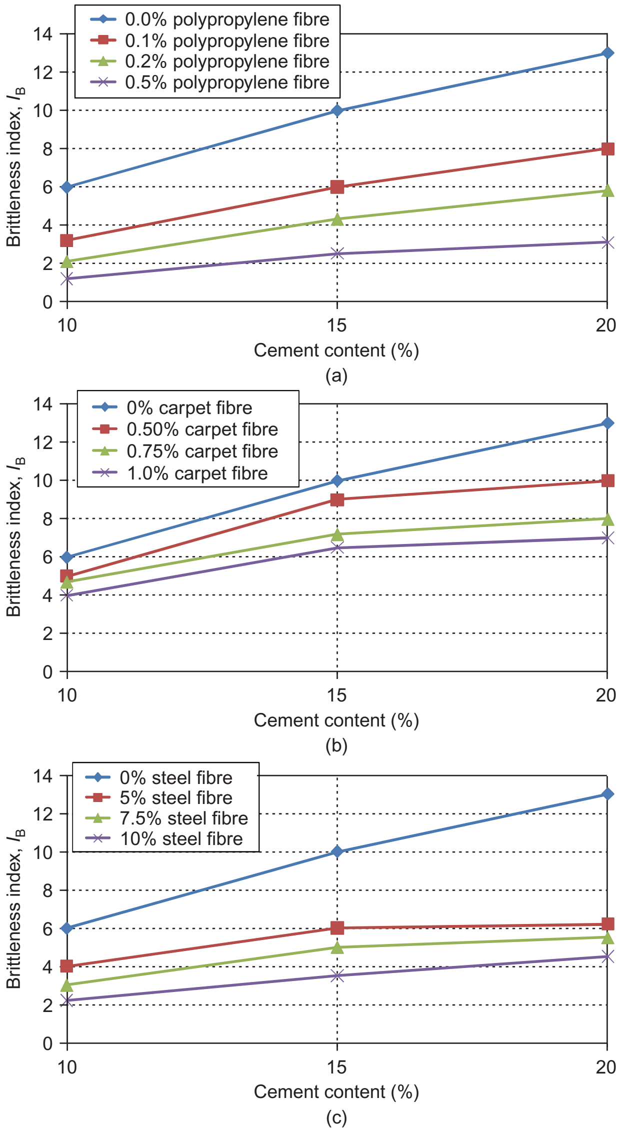


Figure 9. Variation of brittleness index of kaolinite–cement mixture with: (a) polypropylene fibre; (b) carpet fibre; (c) steel fibre

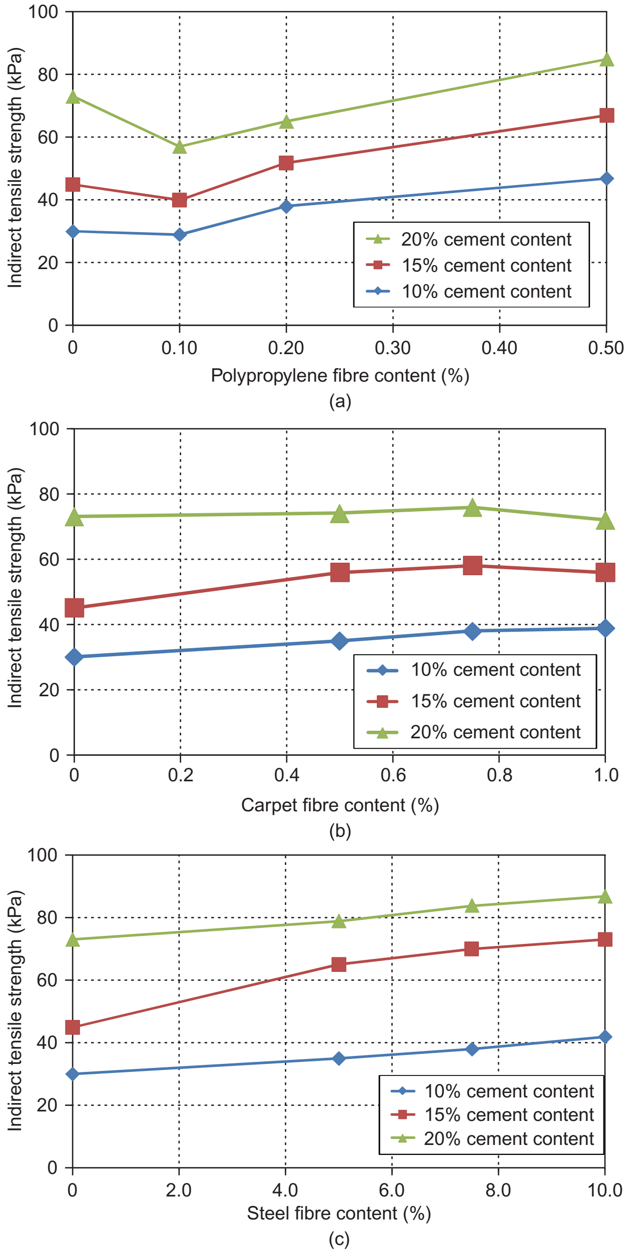


Figure 10. Variation of indirect tensile strength of kaolinite–cement mixture with: (a) polypropylene fibre; (b) carpet fibre; (c) steel fibre

addition, it is believed that carpet fibres may absorb more water than the other two fibres, reducing the water–cement ratio, and hence contributing to a more brittle behaviour.

Figure 10 shows the results of indirect tension tests on 90 cylindrical samples. As expected, the tensile strength of the treated soil increases significantly with increasing cement content. As shown in Figure 10a, the tensile strength of the soil decreases slightly, or does not change, with the addition of 0.1% polypropylene fibres to the cement-treated clay, but then increases with further addition of polypropylene fibres. Figures 10b and 10c show that the tensile strength of the samples increases with the addition steel and carpet fibres. For example, in samples treated with 20% cement, the addition of 0.75% carpet fibres and 10% steel fibres increases the unconfined compressive strength by 15% and 20%, respectively.

Figure 11 shows the ratio of unconfined compressive strength to indirect tensile strength (UCS/ITS). As for he other tests, for each type of fibre, three different cement contents were applied, and corresponding to each cement content, 12 tests were conducted within the previously described ranges of reinforcement fibre contents.

Although there is no particular pattern detected in the variation of UCS/ITS with cement or fibre content in this study, the ratio varies between 6.3 and 9.8, 5.7 and 7.9, and 4.4 and 7.1, for cement-treated kaolinite reinforced with polypropylene, carpet and steel fibres, respectively. As can be seen from these figures, there is no linear relationship between UCS/ITS and cement content. However, it can be seen that the highest values of UCS/ITS are associated with polypropylene fibres added to the treated

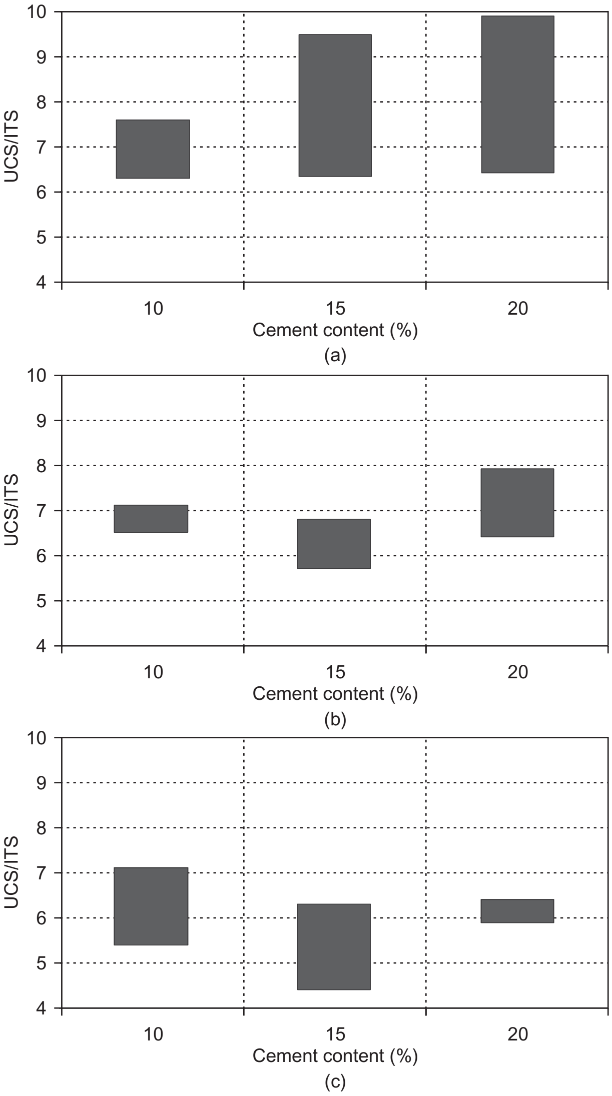


Figure 11. Variation of UCS/ITS of kaolinite–cement mixture with: (a) polypropylene fibre; (b) carpet fibre; (c) steel fibre

clay samples. Kumar *et al.* (2007) reported that the ratio of split tensile strength and unconfined compressive strength increases with an increase in fibre content, which shows that polyester fibres are more efficient, when soil was subjected to tension rather than to compression.

It is well known that rusting of steel fibres in the mix occurs over the long term. Similar to concrete reinforced with steel fibres, the rusting of fibres in the mix may take more than 10 years, and depends very much on the water availability. Some of the water available in the mix will be used in the hydration process. According to Johnston (1982), in some applications such as shotcrete, particularly ones in which staining is aesthetically undesirable, a thin coating of plain shotcrete, applied monolithically on top of the fibrous shotcrete, has successfully overcome the rusting problem. Considering the curing time of 14 days involved in this study, rusting of steel fibres in this period is not expected. However, for practical cases with long lifetimes, this issue may need to be addressed.

The results obtained are of significant value, as the current literature does not address the potential of fibres to be used in conjunction with DSM technology to achieve the required design strength in clay soils. Previous research has focused primarily on the strength gains associated with introducing a cementitious admixture to clay. Although the use of fibres in concrete columns is an accepted industry practice, literature investigating the effects of the fibres on the mechanical properties of the soil–cement columns is scarce. This study covers different cement contents with various fibre contents, and clearly shows that the addition of fibres can be adopted to reduce the required cement content for clayey soils, particularly in applications where the bearing capacity resulting from poor soil strength and ductility of the material is the primary challenge to be overcome.

5. CONCLUSIONS

There is a clear trend in geotechnical construction to develop cost-effective technologies such as deep soil mixing by the addition of waste products and fibres, which may improve the stress–strain and strength properties of the ground. In this study, the effects of various polypropylene, recycled carpet and steel fibre contents on the unconfined compressive and indirect tensile strength of cement-treated kaolinite have been investigated.

The unconfined compression test results indicate that the shear strength increases with the addition of fibres, and the brittle cement-treated kaolinite is changed to a more ductile material. The strength of the cement-treated clay increases with polypropylene fibre content. The change is less pronounced for the samples reinforced with carpet and steel fibres. As expected, both the unconfined compressive and tensile strengths and the stiffness and brittleness of the treated soil increase with the addition of cement. Regardless of the cement content, the addition of polypropylene fibres increases the initial Young's modulus of the samples. However, the stiffness of the carpet- and steel-reinforced cement-treated clay decreases with increasing fibre content, which may be due to the introduction of a material that is more plastic than the cement-treated clay. The results for brittleness index indicate that it increases with cement content, but decreases with fibre content. Indirect tension test (Brazilian) results show that the tensile strength of the soil decreases slightly, or does not change, with the addition of small quantities of polypropylene fibres, but it then increases with further addition of polypropylene fibres. In addition, the tensile strength of the samples increases with the addition of steel and carpet fibres.

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NOTATIONS

Basic SI units are given in parentheses.

a	shape parameter (dimensionless)
D	diameter of sample (m)
E_{f}	Young's modulus of sample at failure stress (N/m^2)
E_{i}	initial Young's modulus of sample (N/m^2)
$E_{50\%}$	Young's modulus of sample at 50% failure stress (N/m^2)
I_{B}	brittleness index (dimensionless)
ITS	indirect tensile strength (N/m^2)
k	ratio of sample thickness to diameter (dimensionless)
L	thickness of sample (m)
P	maximum load applied (N)
Q	axial force at failure (N)
q_{f}	maximum unconfined compressive strength (N/m^2)
q_{r}	residual unconfined compressive strength (N/m^2)
UCS	unconfined compressive strength (N/m^2)
ε_{f}	axial strain at failure point (dimensionless)
$\varepsilon_{50\%}$	axial strain when normal stress is equal to 0.5UCS (dimensionless)
σ_{f}	axial stress at failure (N/m^2)
σ_{r}	residual axial stress (N/m^2)
σ_{T}	tensile strength (N/m^2)

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