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BEHAVIOUR OF FIBRE-REINFORCED AND STABILIZED CLAYEY SOILS SUBJECTED TO CYCLIC LOADING

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Abstract: Much research has been undertaken on the use of fibres to reinforce soils for varying range of applications such as adobe bricks and walls and pavements, but little is available on the response of these materials to repeated loading the subgrade soils in road pavement may be subjected to. Thus, with a view on the application of pavement design, an investigation was undertaken to assess the effect of fibre on kaolinite and laterite stabilised with both cement and lime subjected to repeated loading.

Crimped monofilament of 12 mm long polypropylene fibre with a diameter of 18 microns was used to reinforce both the soils at concentration of 0.3% stabilized with 4% and 6% of lime and cement. Results show that kaolinite soils reinforced with 0.3% of fibres together stabilized with 6% cement under repeated axial load test deform less than 1% after 3,600 load cycles and could be used in pavement construction. For laterite soils under the worst case scenario conditions of soaking, the samples of plain soil and those stabilized with cement did not have enough strength and collapse before loading. However, reinforced and stabilised, particularly were strong enough after soaking to be used in the upper parts of a pavement.

1. INTRODUCTION

Fibres extracted from vegetation of various types have been used for reinforcing soils for thousands of years and in some parts of the world fibres are still used in the construction of bricks for low rise buildings. A number of researchers have considered the effect of using fibres in clayey soils. WIBISONO [14] investigated erosion of fibre-reinforced soil. Other have looked into the improvement in tensile strength of fibre-reinforced soils (GHATAORA et al. [7]) and many have looked into the effect of fibres on strength gain of a range of soils (MAHER and YO [9], RANJAN et al. [11], DALL'AQUA [4], DALL'AQUA et al. [5], GHATAORA et al. [6], PARK and TAN [10], YETIMOGLU and SLABAS [13], and TANG et al. [12]). Most of the researchers have considered the improvements of soil properties under monotonic loading and in many cases only fibre is added. WIBISONO [14], DALL'AQUA [4] and GHATAORA et al. [7], [8] looked into the properties of fibre-reinforced soils with a binder. In general terms, the improvement of the properties of fibre-reinforced stabilized soils is significant. For instance, DALL'AQUA [4] shows that there is a marginal increase in the strength of unstabilized kaolinite. The effect of the fibre on the strength of kaolinite is shown in figure 1, and comparison of plain kaolinite with cement-stabilized kaolinite is shown in figure 2. In all the cases, the materials display a very brittle behaviour. The improvement in kaolinite, when both fibre and cement are added, is shown in figure 3. There was greater than twofold increase in strength. In addition to this, we observe a considerable increase in post-peak strength as a significant strength is retained beyond the peak strength. Mixtures such as these have also shown a high resistance to sheet erosion (WIBISONO [14]).

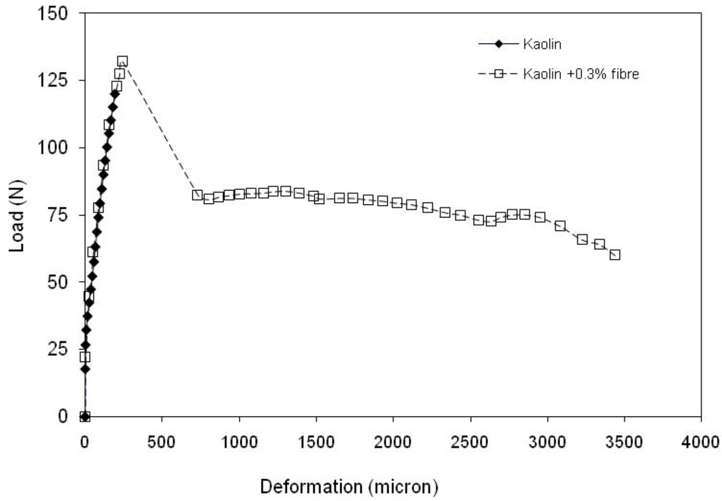

Fig. 1. Load–deformation characteristics of plain and fibre-reinforced kaolinite (DALL'AQUA [4])

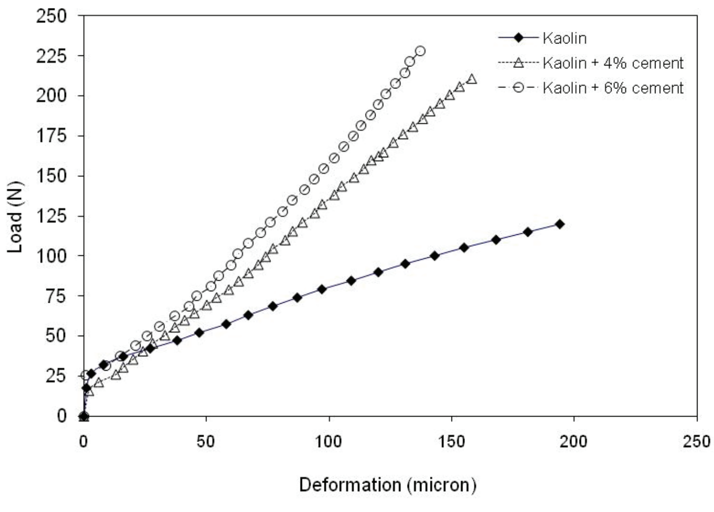

Fig. 2. Load–deformation characteristics of plain and cement-stabilized kaolinite (DALL'AQUA [4])

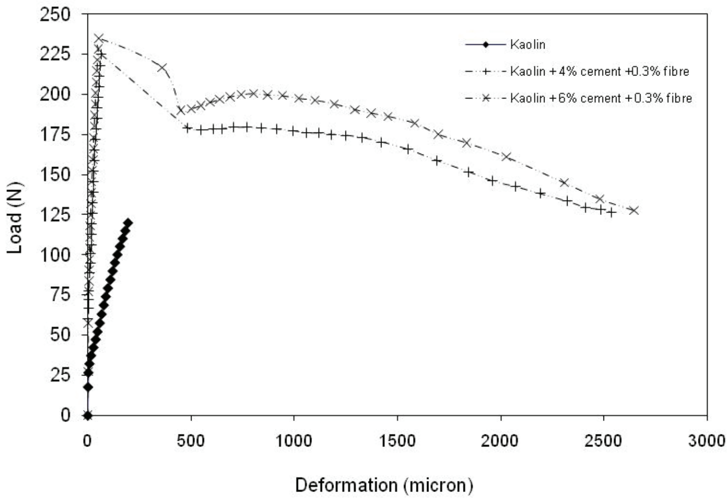

Fig. 3. Load–deformation characteristics of plain and fibre-reinforced stabilized kaolinite (DALL'AQUA [4])

Due to the right content and type of fibre in stabilized soil, the resistance to permanent deformation can be achieved in pavement design. GHATAORA et al. [8] investigated the behaviour of fibre-reinforced kaolinite and laterite soils and showed that inclusion of fibres increased the strength by about 30% and 95%, respectively, when they were compacted at optimum moisture content (OMC). In addition to this, the stabilized and fibre-reinforced soil specimens proved to be more durable when soaked, compared to both stabilized soil (without fibre) and untreated soil.

DALL'AQUA [4] investigated the effect of inclusion of fibres on unstabilized clayey soils and soils stabilized with both lime and cement. These fibres ranged in cross-section from 18 μ to 0.3 mm. The properties of soils with fibre content of up to 0.6% were investigated. He proved that the optimum fibre content approached 0.3% concentration that gave the best performance. Addition of a larger amount of fibres can lead to their uneven distribution resulting in non-homogeneous mix and consequently in the reduction in strength. He also showed that 12-mm long fibres were best, since longer fibres proved difficult to mix.

The research reported herein was aimed at investigating the behaviour of both kaolinite and, to a lesser extent, laterite (due to its limited availability) soils that were reinforced with fibres and stabilized with cement. A small study was undertaken with lime as a stabilizer, but it was not expected to be very effective as its reactivity for strengthening soils is slow. It was envisaged that the main application of such materials would be in road pavement construction.

The design parameter required in addition to strength is the modulus of the soil. If the fibre-reinforced stabilized soil is to be used at the road surface, then it should meet the same criteria as the asphalt surface in the case of thin surfacing layer. Since this related to strain, then if the latter is within acceptable limits for a given load, the material is worthy of consideration for use in road pavement layers. Thus it is inferred that under the worst conditions the results should comply within the maximum value recommended by COOPER et al. [3] for asphalt mix design, where the maximum axial strain measured under repeated axial load should be within 1% after 3,600 load cycles. In addition to this, permanent deformations should be within the maximum acceptable value when soil is compacted at maximum dry density and optimum moisture content.

2. MATERIALS AND MIXES

2.1. SOILS

Processed kaolinite clay (referred to as "kaolinte" in the text) from only one batch was used in this study so that the effect of variability due to soil properties could be reduced. Thus, the effect of inclusion of fibre and cement could be better understood. Additionally, plain laterite (a natural deposit) was used to understand how a natural deposit may behave. Index properties of both the soils are given in table 1. Both soils are silty clays. However, laterite has higher specific gravity than kaolinite.

Table 1

Properties of kaolinite and laterite

Properties	Kaolinite	Laterite
Liquid limit (%)	42	45
Plastic limit (%)	24	21
Plasticity index (%)	16	24
Specific gravity	2.64	2.87
Optimum moisture content (%)	23	13
Maximum dry density (kg/m^3)	1571	2056

All tests were conducted in accordance with BS1377, 1990 (British Standard Institution 1990a).

2.2. FIBRES

Fibre known as "F23" (F23 was manufacturer's designation and it was supplied by Fibrin Ltd. UK) gave the overall best performance in terms of unconfined compressive strength (UCS) and in particular tensile strength (DALL'AQUA [4]). The properties of the F23 fibre are given in table 2. Soils reinforced with F23 were subjected to repeated load.

Table 2

Properties of F23 fibres

Properties	Value/Description	Property	Value/Description
Length (mm)	12	Density (g/cm^3)	0.91
Diameter (μm)	18	Tensile strength (MPa)	37
Type	Micromonofilament	Water absorption	Nil
Polymer	Polypropylene	Softening point (^{o}c)	160
Shape	Crimped	Surface area (cm^2/g)	0.24

2.3. LIME AND CEMENT

Clayey soils can soften due to increase in moisture content. The magnitude of the reduction in strength depends on the type of clay and both the fraction of clay present and the amount of water added. Thus any reinforcement that relies on both friction and cohesion for strength will become less effective as water content is increased. In order to overcome this drawback, the use of both lime (quick lime) and cement (Portland cement) as binders was considered.

In order to estimate the amount of the lime required, initial lime consumption test was undertaken in accordance with the BS1924, 1990 (British Standard Institution, 1990b). The results of the tests give an indication of the maximum amount of the lime required for soil modification. A greater amount of lime will contribute to strength gain. In the case of kaolinite, the initial consumption of both cement and lime was approximately 3.2%. Therefore, 4% and 6% concentrations of binders were used with fibre reinforcement to ensure that their amount was adequate to produce the stabilizing effect. The same concentrations were used for laterite soils. An initial lime consumption for the laterite was about 2%.

2.4. MIXES INVESTIGATED

Eight mix compositions were examined during this investigation (table 3). All specimens for cyclic load tests were prepared by using static compaction technique. (Fixed mass of soil was compacted to obtain a predetermined volume using a hydraulic ram). The specimens were 90 mm high with the diameter of 100 mm to suit the Nottingham Asphalt Test (NAT) apparatus (supplied by Cooper Research Technology Ltd. UK). The kaolinite + cement + fibre and kaolinite + fibre + lime samples were prepared, sealed with cling film and stored in high humidity environment at 20 °C for 28 days. Subsequently, a set of these samples was immersed in water for 7 days for durability testing. For laterite soils, the samples were cured in cling film (sealed) and cured for 7 days in a humid environment followed by 4-day immersing in water. (All the results obtained from soaking tests are referred to as “soaking” in the text).

Table 3

Mix compositions

1	Kaolinite + fibre	5	Kaolinite + fibre + lime
2	Kaolinite + cement	6	Laterite + cement
3	Kaolinite + lime	7	Laterite + fibre + cement
4	Kaolinite + fibre + cement	8	Laterite + fibre

3. TEST RESULTS

In general, four specimens were prepared for each test and normally it was sufficient to test three specimens since the repeatability of the results was exceptionally good.

3.1. COMPRESSIVE STRENGTH OF KAOLINITE SUBJECTED TO MONOTONIC LOADING

A comparison of dry density–moisture content relationship for kaolinite, kaolinite+0.3% fibre, kaolinite+6% cement and kaolinite + fibre + cement is shown in figure 4. The results reveal that the inclusion of cement gives a marginal reduction in the density of the mixture; whereas fibres alone do not have any significant effect. The addition of cement results in a small increase in the optimum moisture content of the soil. Soils were mixed at a range of moisture content and cured for 28 days before determination of their unconfined compressive strength (UCS). Typical strengths for 6% cement and 0.3% fibre are shown in figure 5. Maximum UCS occurred at moisture-compacted couple of percentages below the optimum moisture content (determined from a compaction test shown in figure 4).

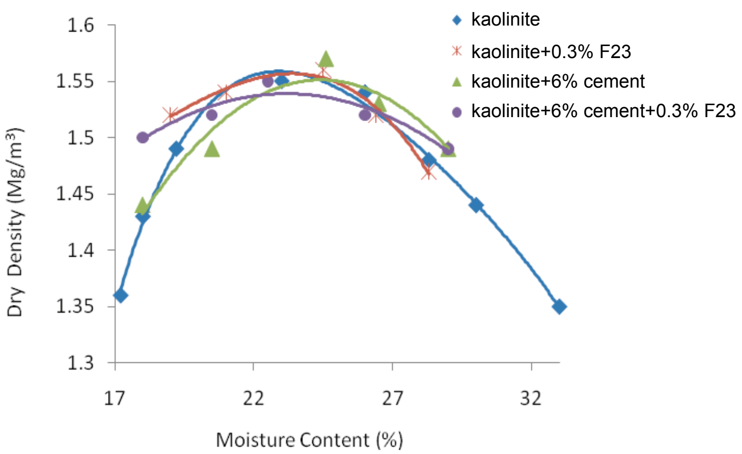

Fig. 4. Relationship between dry density and moisture content of kaolinite

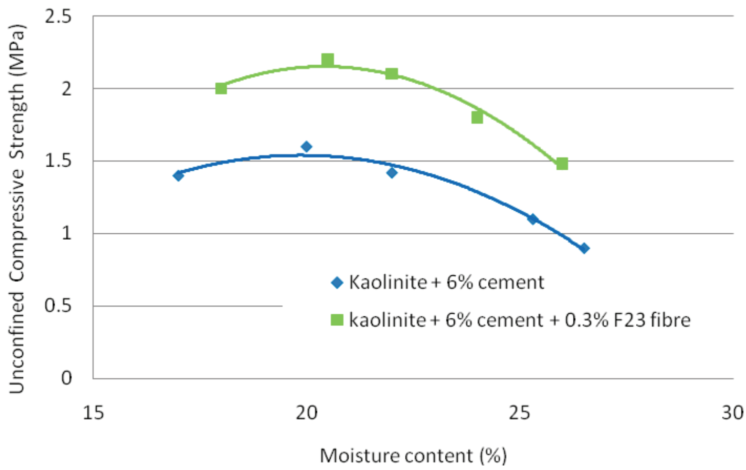

Fig. 5. Unconfined compressive strength–moisture content curves for kaolinite plus 6% cement and kaolinite plus 0.3% fibre and 6% cement

3.2. BEHAVIOUR OF FIBRE-REINFORCED SOILS SUBJECTED TO REPEATED LOADING

Resistance to deformation of the specimens subjected to repeated axial load was assessed using the NAT apparatus. This apparatus is designed to measure the deformation properties of asphalt under cyclic loading. Since fibre-reinforced soils were being considered for upper pavement layers, NAT was considered to be suitable for examining the behaviour of the materials. As no literature has been found on the study of plain or stabilized soil using the NAT apparatus, the results of this investigation are assessed in terms of the results for asphalt mixture. NAT allows us to subject specimens to load cycle which is two seconds long: one-second load period is followed by one-second rest period. Prior to the actual test, the specimen was subjected to a ten-minute initial conditioning where an axial stress of 10 kPa is applied. This is carried out to bed the platens and thus to reduce the bedding-in deformation errors at the beginning of the test. In accordance with this, following the initial conditioning period, the specimen height varies, depending on the specimens with different amount of fibre or stabilizer. With the initial conditioning load likely to cause initial deformations, the test is based on actual strains not taking into consideration the strain induced during the initial conditioning period. All the specimens were prepared at optimum moisture content and maximum dry density.

Test conditions implemented were as follows:

Axial test stress, 100 kPa.
Conditioning stress, 10 kPa.
Conditioning period 10 minutes.

Test duration, 10,000 load cycles
Load cycle, one-second stress duration, one-second rest duration.
Conditions are fixed by equipment manufacturer.

3.2.1. CYCLIC LOAD–DEFORMATION BEHAVIOUR OF KAOLINITE WITH FIBRE AND CEMENT

Deformation of specimens based on actual strain (not taking into account strains induced during the initial conditioning period) are shown in table 4 and a typical deformation–load cycle relationship is shown in figure 6. It can be observed that in reinforced specimens the strains are reduced for 0.3% fibre content. This seems to confirm the earlier observation of increasing fibre content leading to uneven distribution of fibres. Besides this, kaolinite with 0.3% fibre content also shows the least change in axial strain from 1.1% to 1.9% (table 4). Cement stabilized specimens show lower permanent deformation than those containing fibres. However, all the specimens tested with cement only failed when soaked. For the soaked specimens, the best strength performance was achieved with 6% cement and 0.3% fibre where at 3,600 cycles permanent strain was less than 1%. Thus it meets the recommendation made by COOPER et al. [3] for base course and road base mixes. They suggest that resistance to permanent deformation should not exceed 1% axial strain after 3,600. The results presented in table 4 also show that the reinforced stabilized specimens were the only mixes which could undergo soaking tests where the bond strength and friction between the stabilised clay and fibre were no doubt helping to maintain the integrity of the specimens.

Table 4

Permanent deformation for kaolinite reinforced with F23 fibre and stabilized with cement

Composites of materials	Axial strain			
	3,600 cycles		10,000 cycles	
	Microns	%	Microns	%
Kaolinite	3618	4.5	4199	5.2
Kaolinite + 0.2% F23	849	1.0	1632	2.0
Kaolinite + 0.3% F23	890	1.1	1563	1.9
Kaolinite + 0.4% F23	1024	1.3	2268	2.8
Kaolinite + 4% cement	534	0.7	714	0.9
Kaolinite + 4% cement (soaked specimen)	F	–	F	–
Kaolinite + 4% cement + 0.3% F23	2120	2.6	2433	3.0
Kaolinite + 4% cement + 0.3% F23 (soaked specimen)	4127	5.2	4822	6.0
Kaolinite + 6% cement	509	0.6	694	0.9
Kaolinite + 6% cement (soaked specimen)	F	–	F	–
Kaolinite + 6% cement + 0.3% F23	1013	1.3	1219	1.5
Kaolinite + 6% cement + 0.3% F23 (soaked specimen)	724	0.9	1125	1.4

F – failed specimen.

According to DALL'ACQUA [4] the stress level of 100 kPa used to assess the permanent deformation of samples immersed in water is too severe if the end use is considered to be a subbase layer. Nonetheless, the performance of kaolinite reinforced with 0.3% F23 and stabilized with 6% cement was well above the minimum requirements for upper layer of the pavements where the samples were within the 1% limiting deformation and could withstand the stresses applied. It is also suggested that this stabilized and reinforced kaolinite can be used for a more demanding structural pavement layer, such as the subbase.

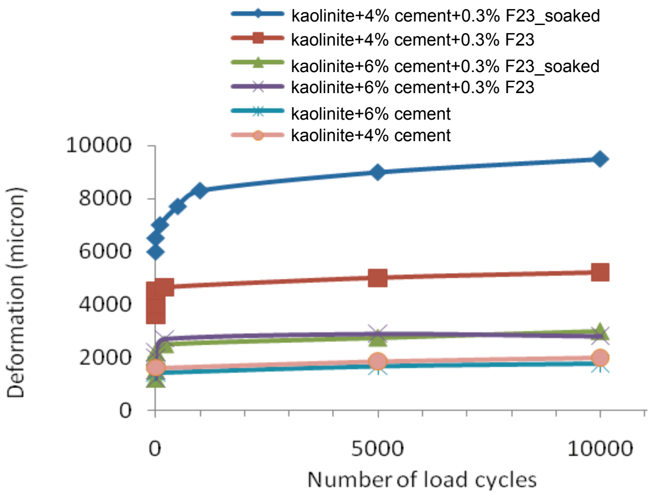

Fig. 6. Relationship between loading cycles and deformation of kaolinite with fibre and cement

3.2.2. CYCLIC LOAD–DEFORMATION BEHAVIOUR OF KAOLINITE WITH FIBRE AND LIME

The results for kaolinite reinforced with 0.3% fibre and both 4% and 6% lime and cured for 28 days are shown in table 4, and a typical deformation–load cycle relationship (for 28 days) is depicted in figure 7. The results show that fibres are responsible for an increase in deformations. This is most probable because of an incomplete bonding between soil and lime. When lime is added to soil, a clayey component flocculates almost immediately. With time, in an environment of high pH, clay minerals react with calcium to form cementitious products. The cementitious reaction is slow and after 28 days does not lead to an adequate improvement in strength. This lack of strength can be observed in figure 7, where specimens with lime are deformed more than those without.

As with cement-stabilized kaolinite, so with lime-stabilized specimens that fail when they were submerged in water to assess their durability. In this instance, even specimens reinforced with fibres failed to survive immersion in water. This was most probably due to the slow reactivity of lime with clay in terms of strength. However in practice, early strength gain is important to allow construction to proceed more rapidly. Thus, lime was not considered to be a suitable binder for kaolinite in instances, where early strength is important.

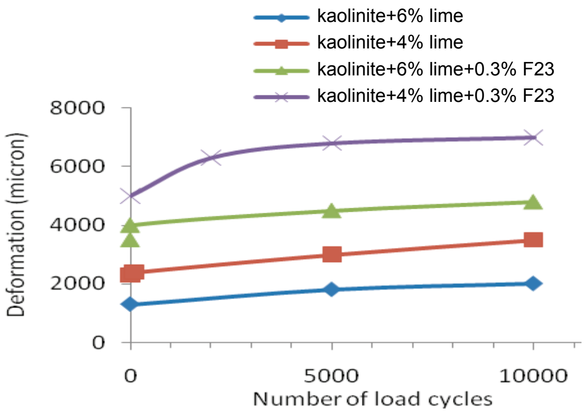

Fig. 7. Repeated axial load test results for kaolinite with fibre and lime after 28 days

3.3. STRENGTH OF LATERITE

3.3.1. COMPRESSIVE STRENGTH OF LATERITE SUBJECTED TO MONOTONIC LOADING

Typical stress–strain curves representing the UCS for both plain and reinforced laterite compacted at OMC and maximum dry density are shown in figure 8. The results show that there was approximately two-fold increment in strength and strain to failure when fibre was added. In addition to this, whilst the unreinforced laterite displayed a brittle behaviour, reinforced specimen exhibited plastic deformation retaining about 80% of its strength at 8% strain. According to DALL'ACQUA et al. [4], there was a significant increase in tensile strength of laterite when fibre was added and that up to 50% of its tensile strength was retained upon soaking. An important result was that there was no significant reduction in the strength of the specimen containing both fibre and cement during the soaking tests which indicated the bonds developed between fibre, cement and soil were substantially water resistant.

Load–deformation curves of laterite, cement-reinforced laterite, cement-stabilized and fibre-reinforced laterite, unsoaked and soaked specimens are shown in figure 9. The results show that reinforcement and cement gave the highest strength and that soaking had little effect on the strength of fibre-reinforced stabilized soil. Laterite proved to be very durable. This response was similar to that of kaolinite.

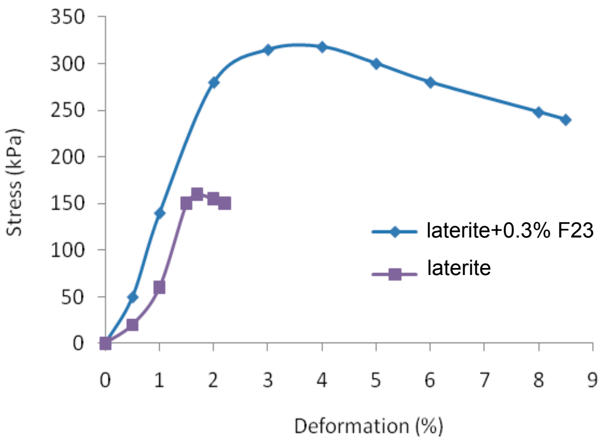

Fig. 8. Compressive stress–deformation curves for plain and reinforced laterite subjected to unconfined compression

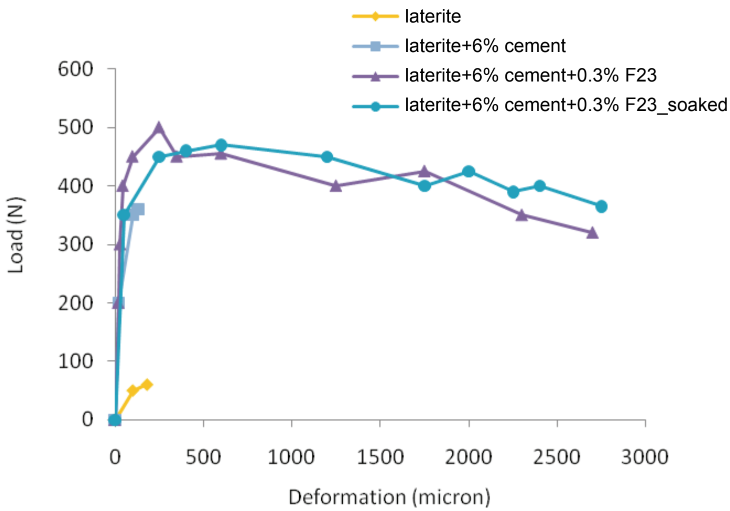

Fig. 9. Load–deformation curves of laterite, laterite + cement and laterite with both fibre and cement

3.3.2. BEHAVIOUR OF LATERITE SUBJECTED TO CYCLIC LOADING

In the study of the strength of soaked specimens, only 0.3% fibre and 6% cement were used. Specimens were prepared as those for kaolinite, described earlier, and also tested using the NAT. The results of permanent deformation at both 3,600 and 10,000 cycles are shown in table 5 and a typical relationship between deformation and load cycles is shown in figure 10.

Table 5

Permanent deformation of stabilized and reinforced laterite

Composites of materials	Axial strain			
	3,600 cycles		10,000 cycles	
	micron	%	micron	%
Laterite	6210	7.7	9631	11.9
Laterite durability (soaked specimen)	C		C	
Laterite + 0.3% F23	872	1.1	1281	1.6
Laterite + 0.3% F23 (soaked specimen)	NS		NS	
Laterite + 6% cement	875	1.1	1103	1.4
Laterite + 6% cement + 0.3% F23	1100	1.3	1350	1.6
Laterite + 6% cement + 0.3% F23 (soaked specimen)	1362	1.7	1450	1.8

C – collapsed, NS – no strength.

As in the case of kaolinite, the durability of the laterite specimens was assessed by their curing in the air and then immersing in water. As can be seen in table 5, plain laterite, reinforced laterite specimens and cement-stabilized specimens were not suitable for testing after soaking because the specimens collapsed shortly after soaking. However, when specimens were stabilized and reinforced, they retained measurable strength. The results indicate that the change in deformation of reinforced and stabilized laterite is 0.1%, which suggests its little effect in the long term compared to short term strength. The ability of the specimen to withstand load is mainly due to the fibre ability to act as a "bridge" for transferring loads to the surrounding soil. With the inclusion of cement, shear strength and water resistance of the soil are improved.

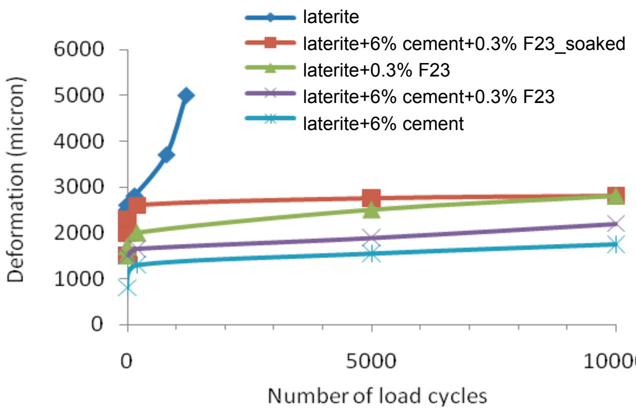

Fig. 10. Deformation–load relationship for fibre-reinforced laterite

It is worth noting that fibres hold the soil together even after failure. Thus soils in a cracked pavement will still retain significant strength. This will prevent the loss of soil, particularly by erosion after a dry spell. This may prove particularly useful in the parts of the world where seasonal climatic effects can lead to the loss of soil used for pavement construction.

4. CONCLUSIONS

The following conclusions were drawn from this investigation on reinforced and stabilized kaolinite and laterite subjected to cyclic loading:

• Inclusion of F23 fibres does not have a significant effect on the relationship between the dry density and moisture content of a soil. However, cement can affect the dry density.

• In both the soils investigated, fibres resulted in a small increase in both strength under monotonic loading and strain to failure.

• Reinforced and cement-stabilized specimens showed an improved resistance to soaking.

• Results showed that cement-stabilized and fibre-reinforced soils may be used in pavement layers. These findings relate to the soils examined (kaolinite and laterite) and may apply to other soils.

REFERENCES

[1] British Standards Institution, *Methods of tests for soils for civil engineering purposes*, BS 1377 British Standard Institution, London, 1990a.

[2] British Standards Institution, *Stabilized materials for civil engineering purposes. Methods of test for cement-stabilized and lime-stabilized materials*, British Standard Institution, London, 1990b.

[3] COOPER K.E., BROWN S.F., PRESTON J.N., AKROYD F.M.L., *Development of a practical method for design of hot-mix asphalt*, Transportation Research Record 1317, TRB, National Research Council, Washington, 1991, 42–52.

[4] DALL'ACQUA G.P., *Fibre Reinforced Stabilized Soil*, PhD Thesis, University of Birmingham, Birmingham, 2000, United Kingdom.

[5] DALL'ACQUA G.P., GHATAORA G.S., FREER-HEWISH R.J., *Behaviour of cement stabilised fibre reinforced Kaolinite and Laterite*, EuroGeo 2000, Bologna, 2000, Italy, Vol. 1, 385–389.

[6] GHATAORA G.S., DALL'ACQUA G.P., FREER-HEWISH R.J., *Effect of crimped fibres and lime on the engineering properties of Kaolinite*, 4th International Conference on Ground Improvement – Geosystems, Helsinki, 2000, Finland.

[7] GHATAORA G.S., CHAPMAN D.N., SCHAD M., AST W., *Influence of Fibres on Properties of Cement Stabilised Sands and Clay*, XIII European Conference on Soil Mechanics and Geotechnical Engineering, Prague, 2003a.

[8] GHATAORA G.S., FREER-HEWISH R.J., DALL'ACQUA G.P., *Flexural Strength of Kaolin Clay Reinforced with Synthetic Fibres and Stabilised with Lime and Cement*, XIII European Conference on Soil Mechanics and Geotechnical Engineering, Prague, 2003b.

[9] MAHER M.H., HO Y.C., *Mechanical properties of Kaolinite fibre soil composite*, Journal of Geotechnical Engineering, ASCE, 1995, Vol. 120, No. 8, 1381–1393.

[10] PARK T., TAN S.A., *Enhanced performance of reinforced soil walls by the inclusion of short fibre*, Geotextiles and Geomembranes, 2005, 23, 348–361.
[11] RANJAN G., VASAN R.M., CHARAN H.D., *Probabilistic analysis of randomly distributed fiber-reinforced soil*, Journal of Geotechnical Engineering, 1996, Vol. 122, No. 6, 419–426.
[12] TANG C., SHI B., GAO W., CHEN F., CAI Y., *Strength and mechanical behaviour of short polypropylene fibre reinforced and cement stabilized clayey soil*, 2006, Department of Earth Sciences, Nanjing University, Nanjing 120093, China.
[13] YETIMOGLU T., SALBAS O., *A study on shear strength of sands reinforced with randomely distributed discrete fibres*, Geotextiles and Geomembranes, 2003, 21, 103–110.
[14] WIBISONO G., *The effect of water content and velocity on the erodability of a fibre reinforced or stabilised kaolin*, MSc Thesis, The University of Birmingham, Birmingham, 2000, United Kingdom.