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Swell-consolidation characteristics of fibre-reinforced expansive soils

B.R. Phanikumar[a,*], Ravideep Singla[b]

[a]VIT University, Vellore 632014, India
[b]Department of Civil Engineering, VIT University, Vellore 632014, India

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Abstract

Many innovative foundation techniques have been devised to counteract the swell-shrink problems posed by expansive soils. Some of these techniques include physical alteration, sand cushioning, cohesive non-swelling soil (CNS) layers, belled piers, under-reamed piers, granular pile anchors and chemical stabilisation. Reinforcing expansive soils with randomly oriented geo-fibres is also an effective technique for controlling the volumetric changes in expansive soils. This paper presents the swell-consolidation characteristics of fibre-reinforced expansive soils. Nylon fibre was used to reinforce expansive soil specimens. One-dimensional swell-consolidation tests were conducted to study the swell-consolidation characteristics of fibre-reinforced clay specimens. The fibre content (f_c) was varied at 0%, 0.05%, 0.10%, 0.15%, 0.20%, 0.25% and 0.30% by the dry weight of the soil. The length (l) of the fibres was varied at 15 mm and 20 mm. The swell potential and the vertical swelling pressure decreased up to f_c=0.25% for both fibre lengths, but increased mildly when f_c was increased to 0.30%. The swell potential and the vertical swelling pressure decreased with an increasing fibre length (l) for all the fibre contents (f_c). The rate of heave for the samples was also found to be in accordance with the above observations. The secondary consolidation characteristics of the fibre-reinforced samples were also studied and compared with those of an unreinforced specimen. It was found that the secondary consolidation characteristics of the fibre-reinforced specimens improved compared to those of the unreinforced specimen.

Keywords: Expansive soils; Fibre-reinforcement; Swell potential; Vertical swelling pressure; Rate of heave; Secondary consolidation

1. Introduction

Expansive soils swell when they absorb water and shrink when water evaporates from them (Chen, 1988; Nelson and Miller, 1992). Due to this alternating swelling and shrinkage, lightly loaded civil engineering structures founded in these soils are severely distressed. The annual cost of damage is estimated at £150 million in the UK, $1000 million in the USA and many billions of pounds worldwide (Gourley et al., 1993). Many innovative techniques have been devised in order to counteract the problems posed by expansive soils. Physical alteration (Phanikumar et al., 2012), belled piers (Chen, 1988) and granular pile-anchors (Phanikumar, 1997; Phanikumar et al., 2004) are some of the innovative foundation techniques adopted for expansive soils. The chemical stabilisation of expansive soils, using lime and fly ash, has also been found quite effective in controlling the volumetric changes in expansive soils (Chen, 1988; Cokca, 2001; Phanikumar and Sharma, 2004). Fly ash columns are a recently developed foundation technique (Phanikumar et al., 2009), which has yielded promising results.

Apart from the above techniques, geosynthetic inclusions as a technique of random reinforcement have also been found

*Corresponding author.
E-mail address: phanikumar_29@yahoo.com (B.R. Phanikumar).
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quite effective in controlling swell and shrinkage (Vessely and Wu, 2002; Viswanadham et al., 2009a, 2009b).

Compacted expansive soils, reinforced with polypropylene fibres, have exhibited reduced tension cracking and controlled volumetric changes due to swelling and shrinkage (Al-Wahab and El-Kedrah, 1995). Ziegler et al. (1998) and Babu et al. (2008) observed that fibre inclusions increased the tensile strength. A combination of fly ash and polypropylene fibres has also been found to reduce the swelling and shrinkage characteristics of expansive soils (Puppala and Musenda, 2000; Punthutaecha et al., 2006; Tang et al., 2007). It has been reported that fibre reinforcement enhanced the unconfined compressive strength and reduced the swelling potential of expansive clays. Cai et al. (2006) observed that an increase in fibre content led to a reduction in the swelling potential of lime-stabilized clayey soil.

The consolidation settlement and swelling of fibre-reinforced samples decreased, whereas the hydraulic conductivity and shrinkage limit increased slightly, when the fibre content and length were increased (Abdi et al., 2008). Ikizler et al. (2008) reported a potential decrease in swelling pressure as a result of the inclusion of expanded polystyrene geofoam placed between an expansive soil and a rigid wall.

Al-Akhras et al. (2008) investigated the effect of two types of fibres (natural and synthetic) on the swelling properties of clayey soils. Nylon and palmyra fibres with different aspect ratios (*l*/*d*) were mixed with three types of expansive soils that had different physical properties. Four aspect ratios ($l/d=25$, 50, 75 and 100) and five different fibre contents ($f_c=1\%$, 2%, 3%, 4% and 5%) were used in the study, and both the vertical swelling pressure and the swell potential were evaluated for each combination. The results of the study showed that an increase in the percentage of both types of fibre reduced the vertical swelling pressure and the swell potential of the clayey soils significantly.

This paper presents the swell-consolidation characteristics of remoulded expansive clay specimens reinforced with randomly distributed nylon fibre. The secondary consolidation characteristics of both unreinforced and fibre-reinforced specimens were also studied. It should be mentioned here that there are quite a few differences between the work done by Al-Akhras et al. (2005) and the work presented in this paper. The fibre contents presented in this paper ranged from 0% to 0.3%, whereas those presented in Al-Akhras et al. (2005) ranged from 0% to 5%. The l/d ratios or the aspect ratios considered in this paper were only 15 and 20, whereas those considered by Al-Akhras et al. (2005) ranged from 25 to 100. Furthermore, in addition to nylon fibre, Al-Akhras et al. (2005) studied palmyra fibre; however, only nylon fibre is considered in this paper.

2. Experimental investigation

2.1. Test materials

Expansive soil of a high free swell index (FSI) was used in the experimental study. Nylon fibre was used to reinforce the expansive soil specimens. Expansive soil was collected at a depth of 1 m from the ground level from the town of Amalapuram, AP, India. The FSI of the soil was 200%. Based on its liquid limit and plasticity index, the soil was classified as CH (high plasticity). Table 1 shows the index properties of the expansive soil. The nylon fibre used to reinforce the soil specimens was randomly oriented as reinforcement. The fibres were twisted monofilament fibres with a diameter of 1 mm.

Table 1
Index properties of the expansive soil.

Specific gravity of soil solids, G_s	2.73
Liquid limit (%)	79
Plastic limit (%)	26
Plasticity index (%)	53
Sand (%)	14
Fraction passing 0.075 mm sieve (%)	86
Free swell index (%)	200
USCS classification	CH

2.2. Test Variables

The dry unit weight (γ_d) of the expansive soil was kept constant at 12 kN/m^3. Oven-dried expansive soil, passing through a 4.75-mm sieve, was used to prepare the test specimens. Hence, the initial water content (w_i) of the specimens was 0%. Oven-dried specimens were used in order to ensure measurable values of the heave and the swell potential. In the case of nylon fibre, the length of the fibre (*l*) was varied at 15 mm and 20 mm. As the diameter of the fibres was 1 mm, the aspect ratio of the fibres used was equal to 15 and 20, respectively. The fibre content (f_c) used in the testing programme was varied at 0%, 0.05%, 0.1%, 0.15%, 0.2%, 0.25% and 0.3% by the dry weight of the soil.

2.3. Tests conducted and quantities determined

One-dimensional swell-consolidation tests were performed in an oedometer on remoulded expansive clay specimens under both unreinforced and geofibre-reinforced conditions to study the effect of fibre reinforcement on the heave, the swell potential and the swelling pressure. The secondary consolidation behaviour of the fibre-reinforced and unreinforced specimens was also studied and compared. The effect of the fibre content (f_c) and the aspect ratio (*l*/*d*) on the above quantities was studied. One-dimensional swell-consolidation tests were conducted by employing the free swell method, wherein the sample is allowed to absorb water freely and undergo heave. In this method, heave is allowed up to saturation or equilibrium heave.

The swell potential ($S\%$) of the samples was determined as the ratio of the increase in thickness (ΔH) to the original thickness (H) expressed as a percentage, as shown below:

$$S\% = \left(\Delta H/H\right) \times 100 \quad (1)$$

The swelling pressure (σ_{vs}) is defined as the vertical pressure required to recompress a fully swollen soil sample to its initial void ratio (e_0). It is determined from one-dimensional swell-consolidation tests, wherein a fully swollen sample is compressed back under vertical compressive stress. Then, the vertical swelling pressure (σ_{vs}) is determined from the e-log σ_v curve as the pressure corresponding to the initial void ratio (e_0). The secondary consolidation characteristics were also studied.

2.4. Test procedure

The samples, under both unreinforced and fibre-reinforced conditions, were compacted in a 1-D consolidation ring (60 mm in diameter and 20 mm in thickness) in four layers of uniform thickness of 5 mm each so that a uniform compaction was achieved and the prefixed dry unit weight was attained by the samples. In the case of the fibre-reinforced expansive soil specimens, the weight of the fibre corresponding to the chosen fibre content (f_c) was thoroughly mixed with the expansive soil, and the mix was compacted uniformly in four layers. The sample was sandwiched between two filter papers and two porous discs. After compaction, the samples were allowed free inundation under a seating load of 5 kPa, and the heave was continuously monitored by a digital indicator attached to the consolidometer. After the equilibrium heave had been reached, the samples were subjected to compression by increasing the compressive loads on the specimen. The samples were then allowed to undergo consolidation under each load increment for 24 h. Compression of the specimens was continued until they reached the initial void ratio. From the e-log σ_v data, the swelling pressure (σ_{vs}) was determined as the pressure corresponding to the initial void ratio (e_0). The secondary consolidation of the unreinforced and fibre-reinforced specimens (for f_c=0.25%; l=15 mm and l=20 mm) was also studied under the applied compressive stress of 320 kPa. The samples were subjected to compression under the above stress for three days to study the secondary consolidation behaviour.

3. Discussion of test results

3.1. Effect of fibre content and fibre length on rate and amount of heave

Fig. 1 shows the rate of heave of the unreinforced and fibre-reinforced expansive clay specimens. The data pertain to a fibre length of l=15 mm at different fibre contents. The data show that equilibrium heave (mm) was attained by the specimens in 3 days or 4320 min. The heave (mm) was found to be the highest for the unreinforced specimen (f_c=0%) at 4.36 mm. However, the heave decreased when the specimens were reinforced with nylon fibre. This could be attributed to the effect of interlocking and to the friction generated by introducing nylon fibre. The heave decreased with an increasing fibre content in the specimens. The data show that the heave decreased up to a fibre content of 0.25%, but increased slightly when the fibre content was increased to 0.30%. When expansive clay specimens are reinforced with randomly distributed nylon fibres, the heave or the upward movement of the samples is controlled because of (i) the interlocking between the soil particles and the fibres and (ii) the friction generated between the soil and the fibres. For the type of expansive soil and nylon fibre used here, the optimum reduction in heave was obtained at a fibre content of 0.25% for l=15 mm. Or, f_c=0.25% can be considered as the optimum fibre content for l=15 mm. The values for heave were found to be 4.2 mm, 4.1 mm, 4.04 mm, 3.9 mm, 3.45 mm and 3.67 mm for f_c=0.05%, 0.10%, 0.15%, 0.20%, 0.25% and 0.30%, respectively, for l=15 mm fibre. For l=15 mm, the heave decreased by 21% when f_c increased from 0% to 0.25%.

Fig. 2 shows the rate of heave profiles for expansive clay specimens under unreinforced and fibre-reinforced conditions. The data pertain to a fibre length of l=20 mm at different fibre contents. The heave decreased with the introduction of fibre inclusions with a length of 20 mm. The heave also decreased with an increase in fibre content for l=20 mm. In the case of l=20 mm also, f_c=0.25% resulted in a maximum reduction in heave. Hence, f_c=0.25% can also be considered as the optimum fibre content for l=20 mm. The values obtained for heave were 4.15 mm, 3.85 mm, 3.55 mm, 3.15 mm, 2.7 mm and 3.24 mm for f_c=0.05%, 0.10%, 0.15%, 0.20%, 0.25% and 0.30%, respectively, for l=20 mm fibre. For

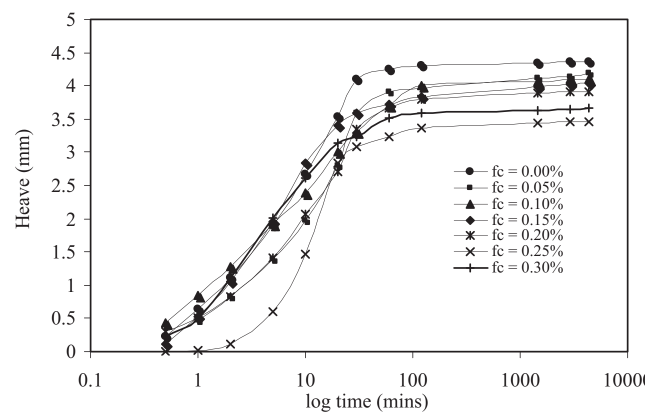

Fig. 1. Rate of heave (l=15 mm).

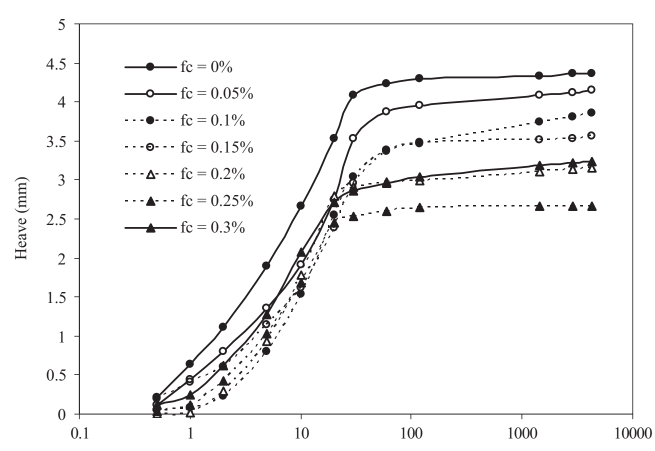

Fig. 2. Rate of heave (l=20 mm).

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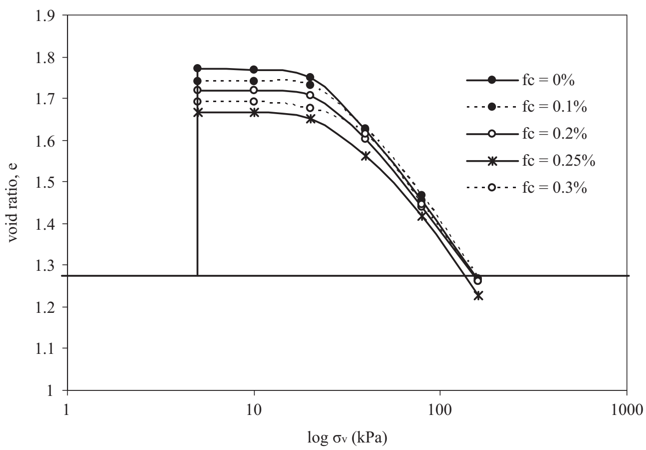

Fig. 3. e-log σ_v curves (l=15 mm).

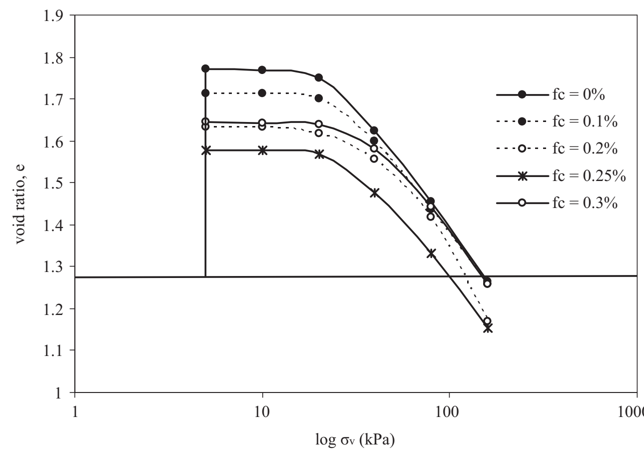

Fig. 4. e-log σ_v curves (l=20 mm).

l=20 mm, the heave decreased by 38% when f_c increased from 0% to 0.25%.

3.2. e-log σ_v curves

Fig. 3 shows the e-log σ_v curves for the unreinforced expansive clay specimen (f_c=0%) and the fibre-reinforced expansive clay specimens for l=15 mm. To avoid a cluster of data, only a few e-log σ_v curves are being shown for comparison. The data shown in the figures indicate that the unreinforced expansive clay specimen attained the highest equilibrium void ratio and that the fibre-reinforced expansive clay specimens attained lower equilibrium void ratios upon saturation through inundation. As was already discussed above in Section 3.1, the fibre reinforcement of the expansive clay specimens induces an interlocking effect and a friction effect, and because of this, the heave decreases. Furthermore, as the fibre content in the sample increases, the heave and the equilibrium void ratio decrease further. Hence, the vertical swelling pressure (σ_{vs}) also decreased with decreasing heave and with increasing fibre content (f_c). The heave decreased up to f_c=0.25%, but increased slightly when the fibre content increased to f_c=0.30%. Hence, the vertical swelling pressure obtained from the e-log σ_v curves of the unreinforced specimen (f_c=0%) and the fibre-reinforced specimens (l=15 mm) also followed a similar trend. The vertical swelling pressure was the highest for the f_c=0% specimen and decreased with an increasing fibre content in the specimen. However, a reduction in the vertical swelling pressure was observed only up to f_c=0.25%; when f_c was increased to 0.30%, the vertical swelling pressure increased. The values for the vertical swelling pressure were equal to 152 kPa, 146 kPa, 134 kPa, 130 kPa and 151 kPa for f_c=0%, 0.10%, 0.20%, 0.25% and 0.30%, respectively, when l=15 mm. Hence, for l=15 mm, the vertical swelling pressure decreased by 14.5% when f_c increased from 0% to 0.25%. The heave and vertical swelling pressure values for f_c=0.05% and f_c=0.15% also fell in a similar trend.

Similar e-log σ_v data were also obtained for l=20 mm at different values for f_c (see Fig. 4). To avoid a cluster of data, only a few e-log σ_v curves are also being shown in Fig. 4. As f_c increased, the heave and the vertical swelling pressure decreased. In the case of the l=20 mm specimens, the vertical swelling pressure decreased from f_c=0% to f_c=0.25% and significantly increased for f_c=0.30%. The values for the vertical swelling pressure were equal to 152 kPa, 142 kPa, 120 kPa, 99 kPa and 150 kPa for f_c=0%, 0.10%, 0.20%, 0.25% and 0.30%, respectively, for l=20 mm. Hence, for l =20 mm, the vertical swelling pressure decreased by 35% when f_c increased from 0% to 0.25%. The heave and vertical swelling pressure values for f_c=0.05% and f_c=0.15% also fell in a similar trend.

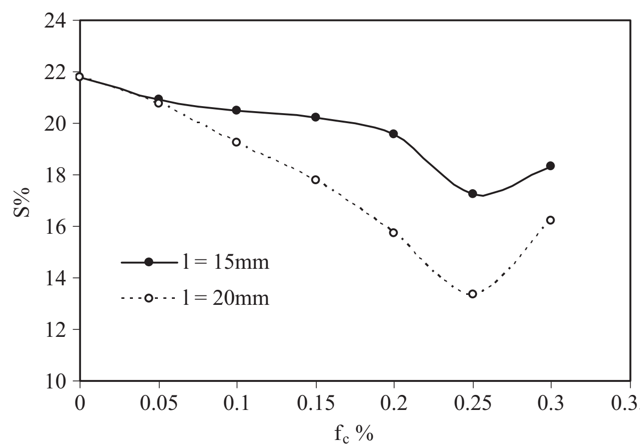

Fig. 5. Variation of swell potential with fibre content.

Fig. 5 shows the variation in S% with the fibre content (f_c%) for l=15 mm and l=20 mm. S% decreased significantly with an increase in f_c up to f_c=0.25%, but increased at f_c=0.30%. This behaviour was found to be true for both l=15 mm and l=20 mm. When f_c was increased from 0% to 0.25%, S% decreased from 22% to 17% and 13.5%, respectively, for l=15 mm and l=20 mm. Fig. 6 shows the variation in vertical swelling pressure with f_c% for l=15 mm and l=20 mm. The vertical swelling pressure decreased with an increase in f_c% up to f_c=0.25%, but increased at f_c=0.30%. This behaviour was also found to be true for both l=15 mm and l=20 mm. The data indicate that, at f_c=0.25%, an increase in the fibre length

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resulted in a significant reduction in the vertical swelling pressure. The vertical swelling pressure (σ_{vs}) decreased from 152 kPa to 130 kPa and 99 kPa, respectively, for $l=15$ mm and $l=20$ mm, when f_c was increased from 0% to 0.25%. Table 2 shows the entire test data.

3.3. Secondary consolidation characteristics

The secondary consolidation characteristics of the unreinforced specimen and the specimens reinforced with nylon fibres of $l=15$ mm and $l=20$ mm at $f_c=0.25\%$ were determined under a compressive stress of 320 kPa. Fig. 7 shows the secondary consolidation behaviour of the unreinforced and the fibre-reinforced specimens (at $l=15$ mm and $l=20$ mm). The data show that the secondary consolidation settlement decreased in the case of the fibre-reinforced specimens. The reduction in secondary consolidation settlement could be attributed to the influence of interlocking and to the friction mobilised in the fibre-reinforced specimens on the way the applied compressive stress is resisted during the secondary time effects. Furthermore, for a given f_c of 0.25%, the secondary consolidation settlement decreased with an increase in the length of the fibre. The primary consolidation ended and the secondary consolidation began earlier in the fibre-reinforced expansive clay specimens than in the unreinforced clay specimen (see Fig. 7). Table 2 shows the secondary compression index (C_α). The value for C_α of the fibre-reinforced specimens was less than that for the unreinforced specimen. Hence, the nylon fibre reinforcement of expansive soils is an effective way to reduce the volumetric changes during primary consolidation as well as during secondary consolidation.

4. Conclusions

The following are the chief conclusions drawn from the experimental study.

1. Heave (mm) decreased with an increasing fibre content (f_c) for a given fibre length (l). However, this was found to be true only up to a fibre content of 0.25%; at $f_c=0.30\%$, the heave (mm) increased. The heave (mm) decreased when the fibre length increased for a given fibre content.
2. The swell potential ($S\%$) and the vertical swelling pressure (σ_{vs}) also decreased with an increasing fibre content (f_c) for a given fibre length (l). This behaviour was found to be true only up to a fibre content of 0.25%; at $f_c=0.30\%$, $S\%$ and p_s increased. The swell potential ($S\%$) and the vertical swelling pressure (σ_{vs}) also decreased with an increasing

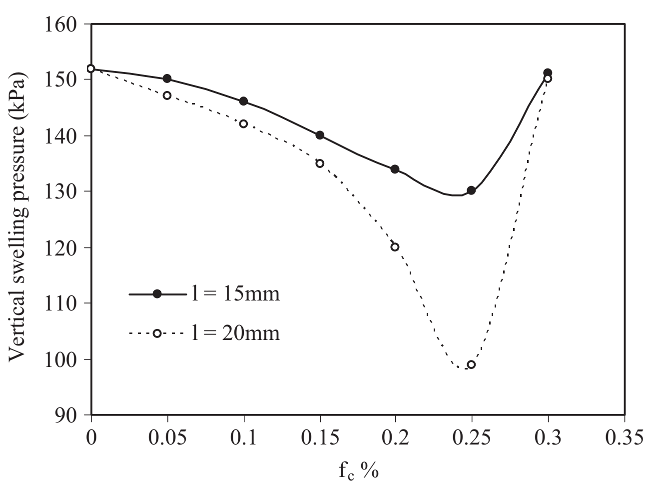

Fig. 6. Influence of fibre content on vertical swelling pressure.

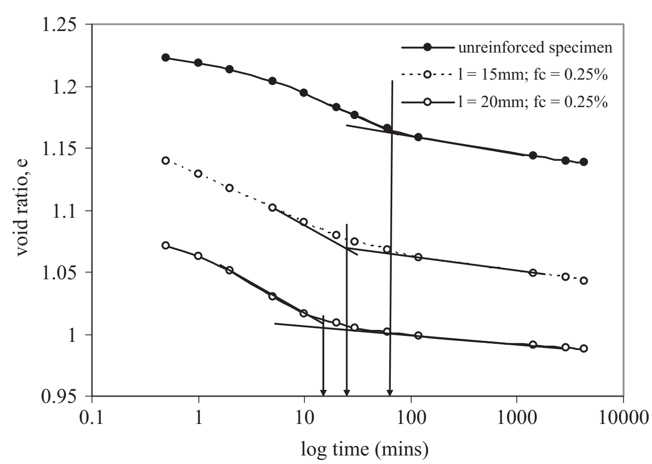

Fig. 7. Effect of fibre reinforcement on secondary consolidation.

Table 2
Summary of test results.

f_c (%)	$l=15$ mm				$l=20$ mm			
	Heave (mm)	Swell potential ($S\%$)	Vertical swelling pressure (σ_{vs})	C_α	Heave (mm)	Swell potential ($S\%$)	Vertical swelling pressure (σ_{vs})	C_α
0.00%	4.36	21.78	152	0.0047	4.36	21.78	152	0.0047
0.05%	4.19	20.93	150		4.15	20.73	147	
0.10%	4.10	20.51	146		3.85	19.25	142	
0.15%	4.04	20.20	140		3.56	17.78	135	
0.20%	3.91	19.56	134		3.15	15.76	120	
0.25%	3.45	17.27	130	0.0041	2.67	13.33	99	0.0025
0.30%	3.67	18.34	151		3.24	16.20	150	

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fibre length for a given fibre content. Hence, for the expansive soil and the type of the reinforcing fibre used here, a fibre content of 0.25% can be considered as the optimum fibre content for both fibre lengths used in the present experimental investigation.

3. The secondary compression decreased in the expansive clay specimens reinforced with nylon fibres. For a given f_c, secondary compression decreased with an increasing length of fibre. The value of the secondary consolidation coefficient (C_α) for fibre-reinforced specimens was less than that for the unreinforced specimen.

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