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Compression Behaviour of Monofilament PVA Fibre Reinforced Cemented Toyoura Sand

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Abstract

In this research work, one-dimensional (1D) oedometer load-unload tests are performed on unreinforced monofilament PVA (poly vinyl alcohol) fibre alone, cement only, and Toyoura sand specimens with fibres and cement to evaluate compression behaviour and obtain critical state line slope (λ), elastic loading and unloading line slope (κ) and K0 normal compression line (N or K0 NCL) parameters. The K0 NCL of monofilament PVA fibre only, cement only, and Toyoura sand specimens containing monofilament PVA fibres plus cement is shown to differ from that of clean cohesionless samples. The addition of additives (fibre and/or cement) to cohesionless soil (Toyoura sand) has no effect on the K0 NCL slope, but increasing the amount of these additives pushes it beyond the K0 NCL of unreinforced sand. It demonstrates that cementitious connections and lock-in influence caused by short discrete/ monofilament PVA fibres are strong enough in contrast to clean sand particles. The migration of the K0 NCL to the right has been recorded in the prior literature for monofilament PVA fibre only, cement only, and Toyoura sand specimens containing fibres and cement. The findings of this investigation are consistent with previous studies.

Keywords: Fibre reinforced sand; cemented sand; oedometer test; normal compression line (NCL).

1. Introduction

Soils have been stabilised with various sorts of additives in numerous geo-environmental projects. Stabilized and reinforced cohesionless soils are composite materials created by combining the qualities of the different constituent materials in an optimal way (Consoli et. al., 2009). Monofilament PVA Fibre and cement additives are frequently used to reinforce soils and improve engineering qualities. Previous researchers used a different types of laboratory tests to investigate the impact of fibre and cement additions in granular soils.

Several soil reinforcing methods were employed to stabilise and increase the physical characteristics of granular soils, but monofilament PVA fibre inclusions are regarded relatively successful method (Al-Adili et. al., 2012). Vidal was the first to offer the notion of increasing the mechanical characteristics of soils in modern soil reinforcement history (1969). Monofilament PVA Fibres were found to offer frictional resistance and increased tensile failure strength. Various fibre qualities impact the efficiency of reinforcement (Wei, 2013). Monofilament PVA fibres can greatly increase the responsiveness of soils under both monotonic and seismic situations, according to previous studies. Other researchers have since conducted more extensive investigations on soils reinforced with other types of fibre inclusions (Haeri et. al., 2006; Consoli et. al., 2011; Diambra et. al., 2010; Ibraim et. al., 2012; Diambra and Ibraim, 2015). More recently, several other researchers (Schmidt, 2015; Safdar, 2018) studied the use of monofilament PVA fibre additives in several ground improvement projects.

Controlling the engineering characteristics of reinforced soil relies heavily on the interfacial mechanical interaction between the monofilament PVA fibre-soil matrix (Tang et. al., 2010). Tang et al. (2010) investigated the interactions of cohesionless soil particles, reinforced with polypropylene

(PP) fibre inclusions. It was concluded that sand, surface area, roughness of monofilament PVA fibre, and composition of soil play an important role (Hejazi et. al., 2012). Figure 1 depicts a hypothetical sand-monofilament PVA fibre interaction process; the starting fibre form is depicted as vertical, simplified representation is shown below. Isotropic compression generates relative movement between particles, resulting in tensile strains in the fibres that connect them. Another cause for monofilament PVA fibre breakage during testing may be the pressing and crushing of the cohesionless soil, which would cut the monofilament PVA fibres stuck between them. This is not, however, the primary process; otherwise, the monofilament PVA fibres would not be expanded (Consoli et. al., 2005). Figure 2 shows a scanning electron microscopy (SEM) picture of an actual monofilament PVA fibre-soil combination, as well as a schematic of fibre-soil interaction.

So far, no information regarding the interaction mechanism has been concluded in a short randomly dispersed monofilament PVA fibre reinforced soil field. Because the discrete/ monofilament PVA fibres used are often weak, and the scattering of fibre additives in cohesionless soils is random and difficult to control (Tang et. al., 2010). As a result, separating and quantifying the interaction mechanism is extremely challenging. The rising use of such geo-reinforcements, however, necessitates a thorough knowledge of the interaction mechanisms at monofilament PVA fibre-soil interfaces.

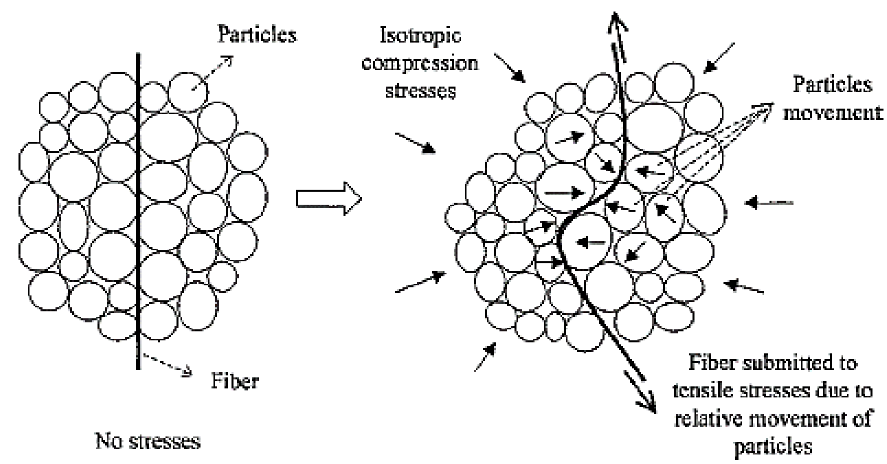

Fig. 1 Particles and Monofilament Fibre Interaction Mechanism (Consoli et. al., 2005).

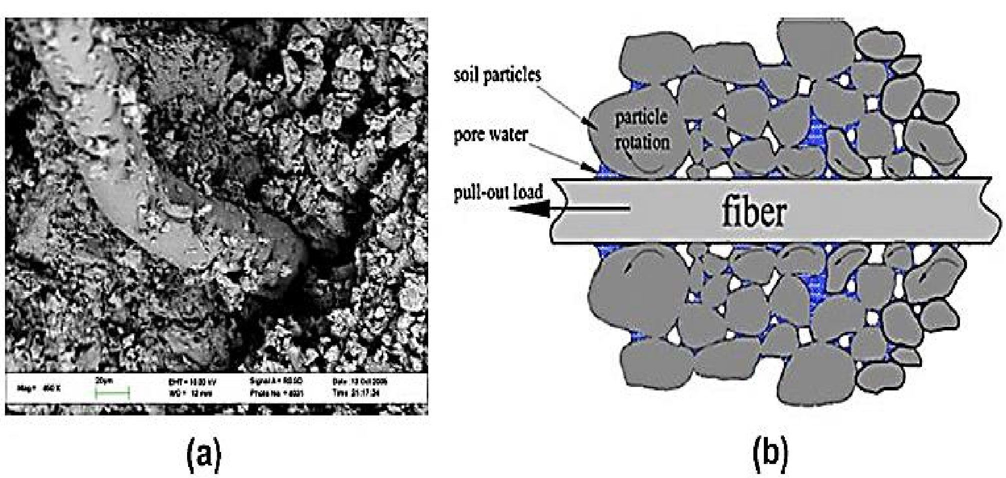

Fig. 2 (a) SEM image of soil particles (b) Interaction mechanism (Tang et. al., 2010)

Another common way for improving the mechanical qualities of soil is to use cementitious material to stabilise it (Sariosseiri and Muhunthan, 2009). Cemented sands' capacity to handle heavy loads, such as for steep natural slopes, is one of its distinctive features (Clough et. al., 1981). In recent years, earth and cement mixtures have been widely employed to produce stable bases beneath rigid bases (Maher and Ho, 1993). Cement additives, in general, have a greater impact on the strength of poor ground, eventually increasing it. Increased cement percentages improve static and dynamic strength (e.g. 0-4 percent by the weight of cohesionless soil). Several research-ers have investigated the peak and post-peak stress-strain (Schnaid et. al., 2001; Sariosseiri and Muhunthan, 2009; Marri, 2010; Porcino et. al., 2011, 2012; Salah-ud-din, 2012; Schmidt, 2015; Safdar, 2018), curing conditions (Consoli et. al., 2009), microstructure (Schmidt, 2015), compression (Salah-ud-din, 2012; Schmidt, 2015; Safdar, 2018; Safdar et. al., 2021) behaviour of naturally and artificially cemented sands.

The majority of the literature related to such soils has concentrated on the shear strength increase (e.g. Michalowski and Cermak, 2003; Lirer et. al., 2012). Monofilament PVA fibre reinforced cemented soils' isotropic/normal compression behaviour has received little attention. Consoli et al., (2005) discovered that soils without monofilament PVA fibre and cohesionless soils with monofilament PVA fibres have distinctive isotropic lines (NCL) that are parallel to each other, with the NCL for the soil reinforced with monofilament PVA fibre, resting above the NCL for the clean cohesionless soil. Santos et al. (2010) observed similar findings and also looked at particle dynamics and discovered that sands reinforced with monofilament PVA fibres broke down less than cohesionless soils. The quantity of breakage, however, was relatively modest since the mineralogy of the sand particles was mostly quartz, and it was not measured. Several studies (Consoli et al., 2005; Santos et al., 2010; Marri, 2010; Salah-ud-din, 2012) examined the compression behaviour of monofilament PVA fibre reinforced geo-materials using high pressure isotropic compression experiments. For monofilament PVA fibre reinforced sands, a single normal compression line parallel to the non-reinforced sand's normal compression line (NCL) was discovered (Pino and Baudet, 2015). As previously mentioned in the literature, fibres have been extensively used in geotechnical engineering. However, there are few investigations on the compression properties of sand+fibre+cement composites in the literature. The influence of monofilament PVA fibres and cement on the compression behaviour of clean sand, monofilament PVA fibre only, cement only, and sand+fibre+cement composites are examined in this study.

2. Testing Overview and Sample Preparation

To evaluate the compression behaviour and obtain λ, κ, and N values for the constitutive model, a series of oedometer load-unload experiments were performed on un-reinforced, monofilament PVA fibre only, cement only and sand+fibre+cement. The testing programme utilised to determine the influence of monofilament PVA fibres and cement content on the compression behaviour of un-reinforced, monofilament PVA fibre only, cement only and sand+fibre+cement is summarised in Table 1. Using the moist tamping technique, samples with dimensions of 50 mm in diameter and 15 mm in height were created in one layer to a desired dry density value (e.g. ρ_d = 1.40 g/cm3) of Toyoura sand. Toyoura sand samples that were un-reinforced, monofilament PVA fibre only, cement only and sand+fibre+cement were manufactured and blended to a water content of 10% by dry mass of soil. The cemented samples were cured for a third time for three days.

The ASTM D2435-04 standard was used to conduct nine oedometer tests. These tests were carried out using a Wykeham Farrance Eng. Ltd. oedometer with a Schaevitz 14.7 mm Linear Variable Displacement Transducer (S/N PCA 116-200) with a resolution of 0.001 mm and an accuracy of 0.2 percent of the full-scale output. Prior to progressive stress increases, specimens were allowed to saturation for 24 hours (50, 100, 200, 400, 800, 1600, 1800, 800, 400, 200, 100, 50 kPa). The oedometer instrument used in this investigation was also utilised in a prior Western University study (Schmidt, 2015).

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2.1 *Tested Materials*

Four different types of material (e.g. Toyoura sand, monofilament polyvinyl alcohol (PVA) fibres, ordinary Portland cement (OPC)) were used in this study to imitate the in-situ soil conditions of the Tokyo Bay region and offer soil amendments. Toyoura sand is a well-known Japanese benchmark sand used in scientific tests (Lam and Tatsuoka, 1988; De and Basudhar, 2008; Schmidt, 2015; Safdar, 2018). Figure 4 depicts a scanning electron microscope (SEM) scan of pure Toyoura sand to highlight particle size, shape, and texture. Toyoura sand is angular to sub-angular and reasonably homogeneous in size when seen under a microscope (Schmidt, 2015; Safdar, 2018; Safdar et. al., 2021).

In this work, synthetic monofilament polyvinyl alcohol (PVA) fibres were employed as fibre inclusions and reinforcing material, as illustrated in Figure 5. PVA fibres outperform monofilament propylene (PP) fibres in terms of chemical resistance, weather resistance, and synthetic tensile strength (Park, 2009).

These cement and fibre additives have previously been employed to simulate in situ recovered gypsum and bamboo fibre characteristics (Schmidt, 2015; Safdar, 2018; Safdar et. al., 2020; Safdar et. al., 2021).

Table 1. Testing program.

Test iNo	***Test iID***	***Cement Content (%)***	***Fibres Content (%)***
1.	NCL-C0F0M0	0	0
2.	NCL-C0F1M0	0	1
3.	NCL-C0F2M0	0	2
4.	NCL-C0F3M0	0	3
5.	NCL-C1F0M0	1	0
6.	NCL-C2F0M0	2	0
7.	NCL-C3F0M0	3	0
8.	NCL-C2F1M0	2	1
9.	NCL-C3F3M0	3	3

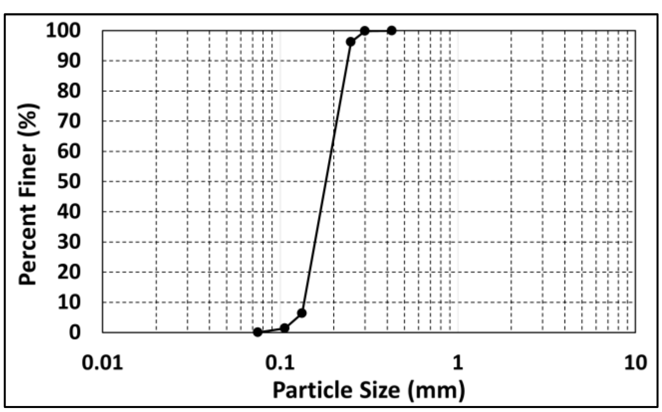


Fig. 3 Grain size distribution curve (Safdar, 2018)

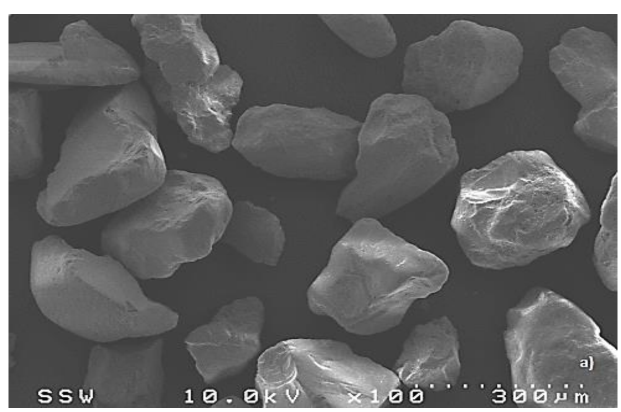


Fig. 4 Toyoura sand SEM Image (Schmidt, 2015)

Fig. 5 PVA fibres (Safdar, 2018)

3. Results and Discussion

Figure 6 depicts the influence of monofilament PVA fibre and cement content on the K0 normal compression line of un-reinforced, monofilament PVA fibre only, cement only and sand+fibre+cement. It demonstrates that the K0 normal compression line of fibre only, cement only and sand+fibre+cement specimens follows a different route from that of unreinforced Toyoura sand specimens. The addition of fibre or cement to pure Toyoura sand has no discernible influence on the slope of the K0 NCL, but increasing the amount of these additives pushes it outside of the unreinforced sand K0 NCL (Consoli et. al., 2005; Pino and Baudet, 2015). Increased cement content, for example, moves the NCL to the right. Furthermore, the K0 NCL (N) intercept increases by roughly 16 percent. The intercept for unreinforced sand is 2.38, whereas the intercept for 3 percent cement and 3 percent monofilament PVA fibre reinforced sand is 2.75 (see Table 2). The random insertion of monofilament PVA fibres into the sand alters not only the shearing but also the compression behaviour of the sand. The monofilament PVA fibre-reinforced and unreinforced sands have two different and parallel normal compression lines. The fibres may be stretched and broken in the monofilament PVA fibre reinforced specimen, suggesting that the monofilament PVA fibres act in tension even when the sample is subjected to significant compressive volumetric stresses and that the monofilament PVA fibres experience considerable plastic tensile deformations before breaking (Consoli et. al., 2005; Safdar, 2018).

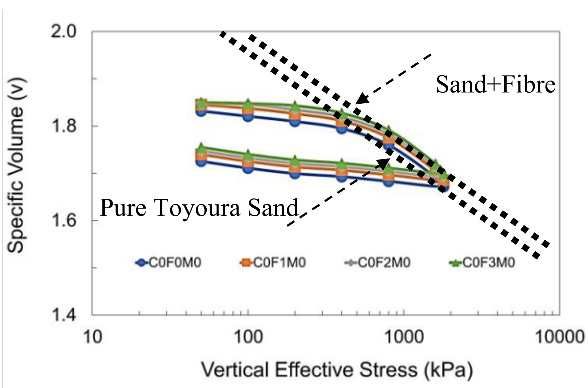
The values of the slope of the critical state line (λ), slope of the elastic loading and unloading line (κ) are obtained from the slopes of loading and unloading, respectively.

The addition of cement to pure sand specimens appears to change the compression behaviour and enhance the amounts of stresses achieved for a given volume (see Fig. 6b). The cemented soils have a strong enough attachment to the particles to allow the cemented samples to reach states beyond the uncemented soil's K0 NCL, which may be thought of as an intrinsic NCL (Santos et. al., 2010). Furthermore, due to monofilament PVA fibre and cement additions, the yield stress is enhanced for a given density, and the site of the K0 NCL is moved outward to higher stresses. Furthermore, monofilament PVA fibre reinforced specimens K0 NCL are displaced to higher stresses as well, but the combination of both cement and monofilament PVA fibre additives results in a larger outward displacement (see Fig. 6c). When monofilament PVA fibres are introduced to cemented sand specimens, the phenomena of outward shift in K0 NCL may be explained to a better control of crack propagation/bond breakdown, resulting in even larger yield stresses at a given density of the specimens.

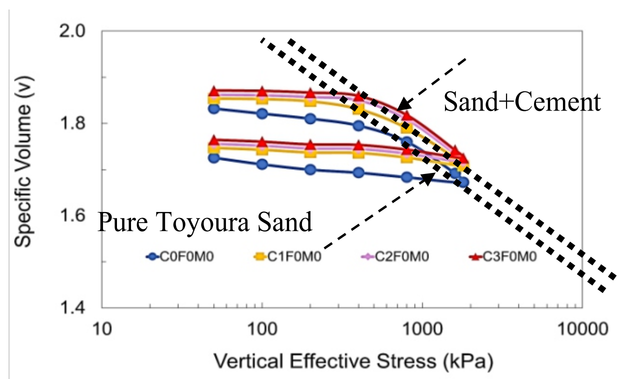
A notable feature is that each material (for example, un-reinforced, monofilament PVA fibre only, cement only and sand+fibre+cement) has its own K0 NCL. Unreinforced sand has a unique NCL, according to a previous study. The addition of monofilament PVA fibres and cement additives to pure sand alters the behaviour dramatically, and different NCLs exist for the various

Table 2. List of λ, κ, and N values for tested specimens

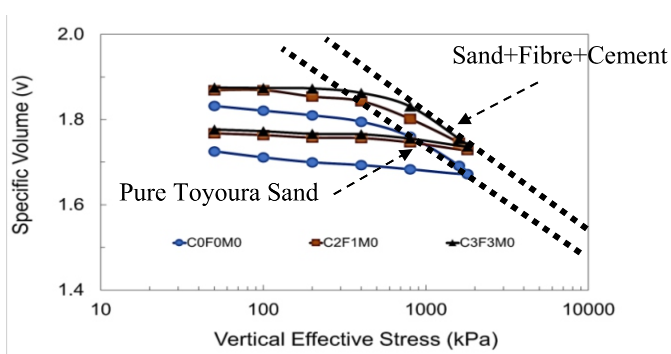
Test No.	*Test ID*	λ	κ	*N*
1.	NCL-C0F0M0	0.143	0.009	2.38
2.	NCL-C0F1M0	0.143	0.010	2.40
3.	NCL-C0F2M0	0.143	0.010	2.43
4.	NCL-C0F3M0	0.143	0.010	2.45
5.	NCL-C1F0M0	0.144	0.008	2.47
6.	NCL-C2F0M0	0.143	0.007	2.52
7.	NCL-C3F0M0	0.145	0.007	2.58
8.	NCL-C2F1M0	0.143	0.007	2.67
9.	NCL-C3F3M0	0.144	0.007	2.75



(a) Pure Sand, and 1-3% Fibres



(b) Pure Sand, and 1-3% Cement



(c) Pure Sand, 2-3% Cement and 1-3% Fibres

Fig. 6. Load-unload curves for tested specimens

materials studied. As a result, the K0 NCL appears to be influenced not only by the geological origin of the soil (e.g. particle size and shape), but also by monofilament PVA fibres and cemented additions.

4. Conclusion

In this work, un-reinforced, monofilament PVA fibre only, cement only and sand+fibre+cement specimens were subjected to a series of one-dimensional compression load-unload tests to evaluate compression behaviour and obtain $\lambda, \kappa,$ and N values for the constitutive model. The route traced by the K0 normal compression line of monofilament PVA fibre, cement, and monofilament PVA fibre reinforced cemented Toyoura sand specimens is demonstrated to be distinct from the path traced by the K0 normal compression line of unreinforced Toyoura sand specimens. The addition of monofilament PVA fibre or cement to pure Toyoura sand has no discernible influence on the slope of the K0 NCL, but increasing the amount of these additives pushes it outside of the unreinforced sand's K0 NCL.

The fact that the NCL of the monofilament PVA fibre-sand combination is higher than the NCL of the sand might be due to the monofilament PVA fibres' lock-in effect, which allows a higher void ratio to exist in the composite material, which is not eliminated under substantial compressive stresses and volumetric strains. This indicates that cementitious linkages and the lock-in effect of monofilament PVA fibres are strong enough in relation to the particles to allow cemented and monofilament PVA fibre reinforced samples to reach states outside the K0 NCL of the unreinforced soil (Cotecchia and Chandler, 2000; Consoli et. al., 2005; Santos et. al., 2010). Table 5.7 shows the values of $\lambda, \kappa,$ and N for un-reinforced, monofilament PVA fibre only, cement only and sand+fibre+cement specimens. This phenomena of the K0 NCL migrating to the right for monofilament PVA fibre, cement, and monofilament PVA fibre reinforced cemented specimens has been documented in the literature, and the results provided in this study are consistent with earlier research (Consoli et. al., 2005; Santos et. al., 2010; Marri, 2010; Salah-ud din, 2012; Lashkari, 2014). This is an intriguing study that will require more research to load-unload K0 NCL at various cement (e.g. curing length) and monofilament PVA fibre concentrations.

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Author's Contribution

Muhammad Safdar and Tim Newson, proposed the main concept and involved in write up. Faheem Shah, assisted in establishing sequence stratigraphy of the section. Muhammad Safdar, collected and analyzed the laboratory data. Faheem Shah, did provision of updated relevant literature, and review and proof read of the manuscript. Tim Newson, did technical review before submission and proof read of the manuscript.

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