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ORIGINAL PAPER

Mitigation of desiccation cracks in clay using fibre and enzyme

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Abstract

Formation of cracks during desiccation is a natural phenomenon in expansive clay. Mitigation of desiccation-induced cracks is highly beneficial for increasing the life span of geo-infrastructures particularly in hydraulic barriers. Improvement of soil properties using additives is a key method in controlling desiccation crack formation and their influence. This paper presents experimental results for an expansive clay modified with nylon fibre and an enzyme-based product. A series of desiccation cracking tests were carried out with varying fibre contents and a constant enzyme dosage. Three-point bending beam tests were performed to evaluate tensile strength of the modified clay. The additives, fibre and the enzyme were able to alter the crack patterns significantly thereby alleviating the effects of cracks. Furthermore, the addition of enzyme alone increased the tensile strength by about 50% while the combined effect of both fibre and enzyme increased the tensile strength by approximately 100% compared with untreated soil. Based on measurement of crack patterns and other properties of the modified clay, the investigation suggests the potential for the fibre-enzyme addition to mitigate desiccation cracks. Further work needs to be carried out to determine optimal dosing requirements for each additive and investigate the effects of potential interactions between the fibre and enzyme.

Keywords Desiccation · Fibre · Enzyme · Tensile strength · Clay

List of notation

ΔT_{fibre}	Tensile strength gain due to fibre addition
C_a	Adhesion of fibre to soil
f_c	Fibre content
w_{cr}	Cracking water content
$\sigma_{n,\ f}$	Normal stress acting on fibre
A, B	Constants
δ	Friction angle between fibre and soil

Introduction

Clay soils are an abundantly used construction material with one of the major applications being the construction of landfill liners and other environmental barrier systems. The primary purpose of these geo-structures is to contain waste and the degrading components (leachate). Almost all of these structures are exposed to natural environment and are subjected to seasonal climatic and weather changes. Compared with other engineering materials such as steel, concrete, and timber, clay soils are susceptible to undergo large strains due to atmospheric changes.

Stresses resulting from restrained shrinkage in clay soils during desiccation can lead to desiccation cracks that will impose severe detrimental effects on geo-infrastructures. In particular, clay liners for waste containment facilities need to ensure an intact liner so as to remain an effective hydraulic barrier to leachate migration. The effects of desiccation cracks, mainly in regard to increased hydraulic conductivity and reductions in the stability of a clay liner, can be devastating for a waste containment facility, as well as for other earth structures (Miller 1988). Hence, the analysis (Tang et al. 2011; Li and Zhang 2011; Morris et al. 1992; Tollenaar et al. 2017), modelling (Pouya et al. 2019; Amarasiri et al. 2011), and test

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development (Costa et al. 2016; Varsei et al. 2016) for desiccation cracking have become a frontier in geotechnical engineering research in the last two decades.

Mitigation or elimination of clay cracking would be extremely beneficial for the functioning of any clay structure. One of the options is to place a moisture barrier on the soil surface to prevent moisture removal. The other option is to alter the soil properties thus reducing the crack potential and the extent of cracking when it does occur. Key soil characteristics in this regard include tensile strength, shrinkage strain, dry density and hydraulic conductivity. In addition, the soil-water characteristics are critical.

Researchers have investigated various additives as soil amendments. Influence of additives such as lime, cement, sand and diatom has been investigated (Omidi et al. 1996; Leung and Vipulanandan 1995; Li et al. 2012). These studies focused on the volumetric shrinkage and hydraulic conductivity of clay soil. The additives were able to reduce soil shrinkage but an increase in hydraulic conductivity was also observed in some cases. A decrease in soil plasticity subsequently increasing cracking potential in compacted clay also was another adverse outcome of the studies. Therefore, the interest of using novel additives has arisen to further improve clay performance while minimising desiccation cracks in clay.

Notable studies have been conducted by adding both natural and synthetic fibres to clay soils as reinforcing agents (Hejazi et al. 2012). Synthetic fibres have been more popular with polypropylene being the most common material (Abdi et al. 2009; Chaduvula et al. 2017; Harianto et al. 2008a; Miller and Rifai 2004; Senol 2012; Shulley et al. 1997; Tang et al. 2012; Thyagaraj and Soujanya 2017) while glass fibre (Maher and Ho 1994), nylon fibre (Estabragh et al. 2011; Kumar and Tabor 2003) and polyethylene fibre (Sobhan and Mashnad 2002) have also been investigated.

The addition of polypropylene fibre reduced the consolidation settlement and shrinkage strain, increased dry density, tensile strength and hydraulic conductivity. However, the exact behaviour of fibre-reinforced soil depends on many factors such as fibre type, shape, length, diameter, texture and the amount of fibre added. Published research is unanimous that a small percentage of fibre, usually less than 1% by weight, is sufficient to generate considerable changes in mechanical properties of soil. Most studies found the optimum fibre content to be in the range of 0.2% to 0.5% by weight. Tang et al. (2016a) reported that wave-shaped fibre has a significant advantage over straight fibre in terms of interface shear strength. In a pullout test, wave-shaped fibre showed 2.8 more shear strength than straight fibre. In the framework proposed by Zornberg (2002), it is assumed that the shear strength of fibre-soil composite is mobilised from the individual shear strength of the soil matrix and the tensile stresses induced by fibres on the shear plane. Thus, the individual properties of soil and fibre can be used to predict the shear strength of the composite (Li and Zornberg 2013).

Fibre addition has been investigated as a stabilization technique for soft soils in combination with other additives. Mirzababaei et al. (2018) studied the compressive strength of clay stabilised with polypropylene fibre, poly vinyl alcohol and butane tetra carboxylic acid. Their results showed significant improvements in compressive strength and ductility. Similar findings have been reported by other researchers (Jamsawang et al. 2018; Onyejekwe and Ghataora 2014) using a variety of fibre types and secondary additives. Fibre-reinforced soil shows greater void ratio than unreinforced soil. Consequently, fibre-reinforced soil exhibits greater resistance to compaction and increased compression index (Choo et al. 2017). Nevertheless, the strengthening loose soil using fibres requires less energy compared with densification of unreinforced soil (Ibraim et al. 2018).

Tensile strength of fibre-reinforced clay is an important parameter in controlling shrinkage crack formation. Fibre addition creates a bridging effect in the soil matrix thereby giving rise to considerable improvements in tensile strength (Tang et al. 2016b). Desiccation cracking tests mixed with polypropylene produced promising results as translated by reduced crack intensity factor and enhanced crack reduction ratio (Kafodya and Okonta 2019; Chaduvula et al. 2017; Tang et al. 2016b; Miller and Rifai 2004). Organic enzymes (often referred to as bio-enzymes) have also been experimented for enhancing soil properties in the recent past (Taha et al. 2013). Focus of these studies was on the stabilization of soil. Increased compressive strength, reduced compaction effort, increased dry density and lower hydraulic conductivity are some of the advantages mentioned. Overall, results indicate modest to significant improvements in soil properties (Taha et al. 2013). For instance, studies by Velasquez et al. (2005) investigated the effect of enzymes on shear strength and resilient modulus. The two enzymes used were able to improve the shear strength of two soil types by 9% to 39%. One of the enzymes had a marked effect on resilient modulus whereas the other enzyme showed a varied influence. Activity of enzymes can be influenced by temperature. Most enzymes become inactive at low temperatures or get destroyed at high temperatures. Renjith (2020) studied the effect of temperature in soil preparation for enzyme stabilization and found out that there is no significant influence up to about 40 °C. In general, literature suggest that the use of enzymes in soil stabilization needs more investigation in terms of soil and enzyme characterization using laboratory tests (Renjith et al. 2017).

However, the effect of enzymes has not been investigated in the context of desiccation cracks. Moreover, while various additives have been investigated for mitigation of desiccation cracks, little to no research has been directed towards the study of the combined effect of more than one additive. The hypothesis behind the current study therefore is that it is possible to enhance the water retention capacity of soil by using enzymes while achieving an increased tensile strength and dry density by adding fibre.

Two types of additives were used in the study: nylon fibre and an enzyme. These additives were mixed with an expansive soil in different combinations, and cracking characteristics were observed during drying. It is expected that the overall effect will be a reduction in shrinkage potential thereby controlling the desiccation cracks. Atterberg limits of treated clay have also been studied. Given that desiccation crack formation is directly related to tensile strength, change in tensile strength upon the addition of fibre and enzyme has also been investigated. This paper presents the results of aforementioned studies and discusses the influence of tested additives on crack initiation, crack intensity and tensile strength.

Materials and experimental setup

Materials

Merri-Creek clay, an expansive clay available locally, was used in the experiments. A soil stabiliser containing enzymes and nylon fibre was selected as additives to be mixed with clay. The experimental setup and a brief description of the materials are given below.

Merri-Creek clay

This heavy and sticky black expansive clay is found in the northeast side of Melbourne, Australia. Merri-Creek clay is believed to be formed by the weathering of basalt of the newer volcanics. Several researchers have studied Merri-Creek clay in the past and its properties can be found in literature (e.g. Costa et al. 2013). The key properties of Merri-Creek clay are given in Table 1.

Table 1 Properties of Merri-Creek clay

Property	Value
Liquid limit	71%
Plastic limit	29%
Plasticity index	42%
Linear shrinkage	21.8%
Specific gravity	2.62
Clay fraction	57%
OMC	23.6%
MDD	1.5 t/m^3
Colour	Grey/black

Nylon fibres

Nylon fibre was used as one of the additives in the tests. The selected fibre is a commercially available mono-filament fishing line, which is made from a single fibre of plastic. Nylon fibre was preferred because of its relatively high tensile strength and abundant availability at low cost. Overall, nylon has an excellent resistance to chemicals and hydrocarbons, which has relevance for landfill applications. Additionally, nylon is effective against corrosion or deterioration in the soil (Estabragh et al. 2011). The selected nylon fibre was rated to 6 lb with a diameter of 0.25 mm. The length of the fibre was selected to be 10 mm based on information available in literature (Harianto et al. 2008a; Maher and Ho 1994).

Enzymes

A number of enzyme-containing products are available in the market today. In the present experiments, a commercially available enzyme-containing product, Eko-Soil, was investigated as the source of enzyme. This product has successfully been used to stabilise unsealed road pavements in Australia (Renjith et al. 2020; Renjith et al. 2017; Singh et al. 2017) and India (Sen and Singh 2015). Eko-Soil is a naturally derived soil stabiliser fermented from organic materials based on the saliva of termites. According to the manufacturer, it is a unique multi-enzyme blend which contains enzymes, surface active agents, various soil nutrients and organic polymers. The active enzymes in the product are lipase, amylase and protease (Norwood Hall 2014). The specific gravity of the product is 1.10 at 20 °C. The product performs well at temperatures under 40 °C. Freezing will not damage the product though temperatures above 40 °C can limit enzyme activity (O'Donnel 2015). The manufacturer of the product claims to increase soil density and load bearing capacity and lower compaction efforts, hydraulic conductivity and maintenance requirements. More details of this liquid soil stabiliser can be found in Mitikie et al. (2017) who used it to improve mechanical properties of clay bricks.

The aforementioned benefits of enzyme addition are achieved by accelerating the cohesive fusing of soil particles via catalytic action, producing a tighter, stronger and less penetrable stratum. When added to the soil-water mix, the active enzymes lipase, amylase and protease catalyse the hydrolytic cleavage of chemical bonds. The quantities needed to achieve this effect vary between 0.15 and 0.5 g per kg of dry soil. The manufacturer suggests that the exact quantity needed should be determined through the use of a compaction test. Based on preliminary tests and manufacturer recommendation, a quantity of 0.35 g per dry kg was considered to be optimum for this work.

Enzymes interact with soil and reduce the thickness of the absorbed water film surrounding the soil particles. This water film contains positively charged metal ions. From the electrochemistry perspective, the first action of the enzyme will be to lower the dipole moment of the water molecule thus dissociating the hydroxyl (OH^-) and hydrogen (H^+) ions. After sometime, further dissociation and association of these ions, along with negatively charged fine colloidal particles, produce sufficient negative charge to break the electrostatic potential barrier in the absorbed water film. As a result, metal ions migrate into the free water which can be removed leading to thinning of absorbed film and reduction in swelling capacity of the soil, as detailed out in Velasquez et al. (2005).

Desiccation cracking tests

Desiccation cracking tests were designed to study the crack patterns in Merry-Creek clay mixed with nylon fibre and enzyme. Circular specimens, similar to the ones presented in the work of Costa et al. (2013), were prepared and dried in glass containers. Merri-Creek clay was dried in the oven, crushed, ground and was passed through 425-μm sieve.

As discussed, 35 g of enzyme per 1 kg of dry soil was used as per manufacturer recommendations. However, the nylon fibre was added in different quantities at 0, 0.3, 0.6, 0.9 and 1.2% using triplicates. These samples were compared with control specimens wherein neither fibre nor enzyme was added. Details of the test program are given in Table 2.

The initial water content of all the specimens was around 85% which was well above the liquid limit (LL). Mixing of materials was done in the following order: first, fibre was mixed with dry soil; secondly, the enzyme was added to the required amount of water; and then, the solution was poured into the soil-fibre mixture. After thoroughly mixing, the paste was placed in a sealed container and left for 24 h to achieve homogenous moisture conditions.

To prepare the test specimens, the soil-fibre-enzyme mixture was poured into 140 mm diameter glass containers and they were patted carefully to expel any trapped air. The thickness of the specimens was set to 10 mm so to be able to obtain a simple and clear crack pattern which is easy to analyse. Specimens with lesser thickness (e.g. 5 mm) tend to provide dense crack patterns while thicker specimens (e.g. 20 mm) generate largely spaced cracks (see Costa et al. 2013).

Floodlights of 500 W were used to expedite the drying process as shown in Fig. 1. The distance between the lamps and the specimen was 500 mm. The constant emission of heat from the lamps kept the surrounding temperature stable at 30 ± 0.5 °C. A digital camera, mounted above the specimen, recorded images at 5 min intervals during the drying process. A digital image analysis software, ImageJ (Abramoff et al. 2004), was used to analyse the images of cracked specimens. A detailed description about using the ImageJ program for image analysis in desiccation cracking can be found in Lakshmikantha et al. (2009).

Tensile strength tests

Three-point bending tests as described in ASTM D790 (2003) were carried out to determine the tensile strength. The quantities and combinations of additives were kept similar to desiccation cracking tests with an enzyme content of 35 g per 1 kg of dry soil and fibre content ranging from 0 to 1.2%. Processing of Merri-Creek clay was also similar to desiccation tests.

Soil was compacted in a rectangular mould (300 × 240 × 55 mm) applying compaction energy equivalent to standard Proctor test. The rectangular block obtained from compaction was cut into small beams with a thin knife. The size of the beams were 100 × 25 × 25 mm with a span of 88 mm. This is in accordance with ASTM D790 that states the span of the support should be no larger than 4 times the width of the specimen (< 4 × 25 mm).

Beam bending test was performed in a horizontal configuration as shown in Fig. 2. A slower loading rate of 0.2 mm/min, which is less than recommended (0.52 mm/min), was applied to avoid a hasty failure.

Experimental results

Atterberg limits

The addition of enzyme changes the Atterberg limits only slightly. The LL of the treated soil was 73%, an increase of just 2% from its original value. A similar increase was evident

Table 2 Different additive combinations

Group	Clay type	Enzyme content (per 1 kg of dry soil)	Fibre content by weight
1	Merri-Creek clay	0	0
2	Merri-Creek clay	0.35 g	0
3	Merri-Creek clay	0.35 g	0.3%
4	Merri-Creek clay	0.35 g	0.6%
5	Merri-Creek clay	0.35 g	0.9%
6	Merri-Creek clay	0.35 g	1.2%

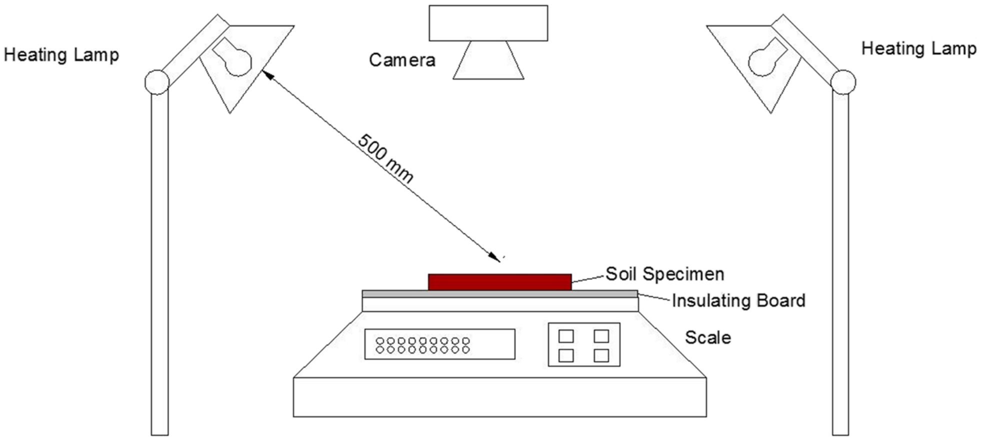


Fig. 1 Desiccation cracking test setup

in plastic limit where it increased from 29 to 31% only. However, this did not change the plasticity of the soil as plasticity index remained the same (42%) between control test and specimen with enzyme.

Characteristics of crack patterns

The experiments were carried out under accelerated drying conditions with the use of floodlights. All the specimens lost moisture at a similar rate in the first phase of drying as it can be seen from the drying curves in Fig. 3. Since the initial water content was well above the LL, it is reasonable to assume that the specimens were fully saturated during this phase (phase 1). The end of this phase is marked by a turning point on the curves around a water content of 75% which is close to the LL. Except for the fibre content, (f_c) = 0.3% curve, the general trend is specimens dry faster when fibre content is higher (phase 2). It can therefore be inferred that addition of fibre promotes the removal of water. The effect of enzyme alone can be seen when comparing the f_c= 0% specimen with the control test. Addition of enzyme slows down the drying process as expected. Also shown in Fig. 3 is the average evaporation rate (percentage loss of moisture content per minute) for all the specimens. Trend of moisture loss rate is similar to desiccation of clay samples without fibre (see Tang et al. 2011). Specimens lose moisture at a uniform rate during phase 1 and phase 2 and at an increasing rate during the transition. The low drying rate in phase 1 corresponds to the initial warming up period of the specimens. A similar phase was observed by Costa et al. (2019). The specimens took nearly about an hour to reach the temperature of the drying environment (30 °C) under lights after being prepared at the room temperature at about 20 °C. Evaporation rate in phase 2 corresponds to uniform drying conditions once the specimens had reached the drying temperature.

Figure 4 shows the crack patterns obtained for different additive combinations at the end of the drying period. Representative samples for each combination out of the three replicates have been presented. The initiation of cracks in clay is often sequential and their propagation is through subdivision (Costa et al. 2008; Nahlawi and Kodikara 2006). Similar phenomena were observed in subject tests using fibre and enzyme reinforced clay. It is evident that specimens with no fibre (Fig. 4 a and b) had less but more pronounced cracks that are longer and wider. The number of cracks increases as the fibre content increases. However, an increased fibre content

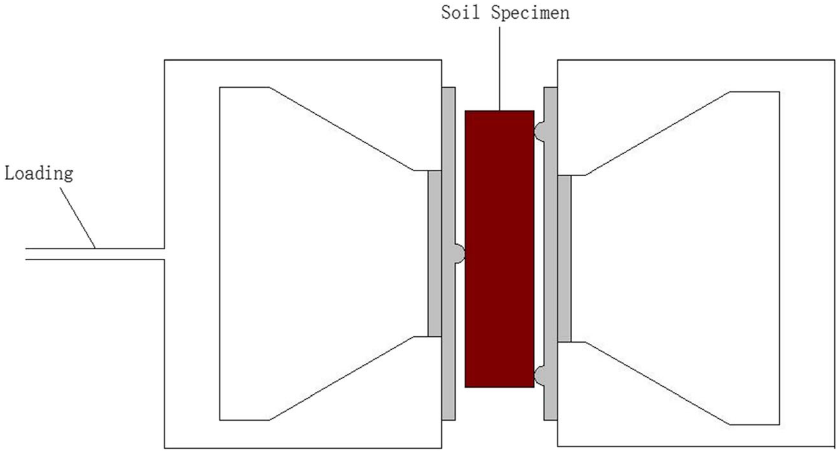
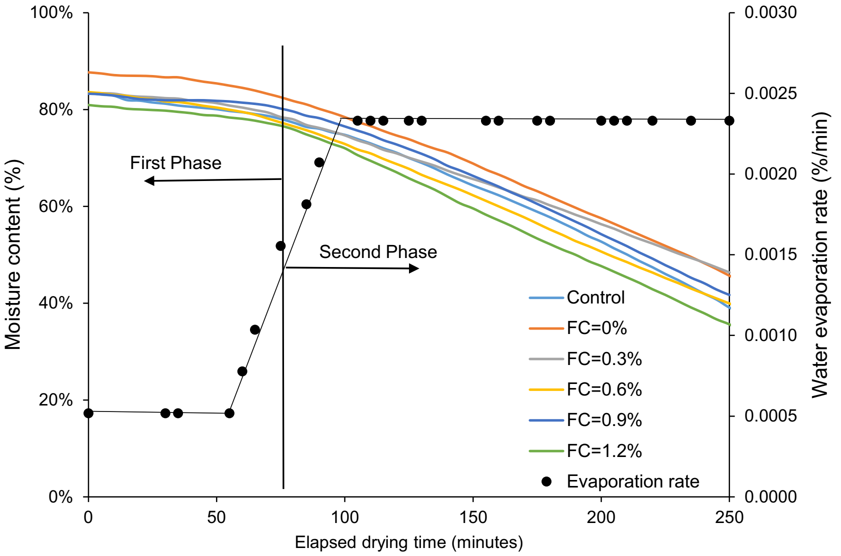


Fig. 2 Three-point bending test setup

Fig. 3 Change of water content and evaporation rate with time in desiccation tests (average from the triplicates is shown)



results in shorter and narrow cracks (Fig. 4 e and f). Average size of uncracked cells also reduces considerably with the increased fibre content. Almost every crack penetrated the full depth of the clay layer in all specimens. This is not uncommon in thin clay layers up to about 20 mm thickness subjected to high drying rates (Costa et al. 2013).

Desiccation cracks in clay usually intersect orthogonally or close to 90° (Corte and Higashi, 1964; Kodikara et al. 2002). Reason for this phenomenon can be explained in the light of maximum stress release criteria (Kodikara and Choi 2006; Morris et al. 1992; Lachenbruch 1961). However, crack patterns in the subject fibre-enzyme reinforced clay were observed to gradually deviate from the expected orthogonal crack intersection pattern. Further comparison of Fig. 4c, d with e, f indicates that more non-orthogonal intersections appear as the fibre content increased. This observation is in line with previous studies using fibre-reinforced clay (Chaduvula et al. 2017; Tang et al. 2012). Since the previous studies included only one additive (i.e. fibre), the formation of non-orthogonal crack patterns may be attributed to the influence of fibre rather than the enzyme.

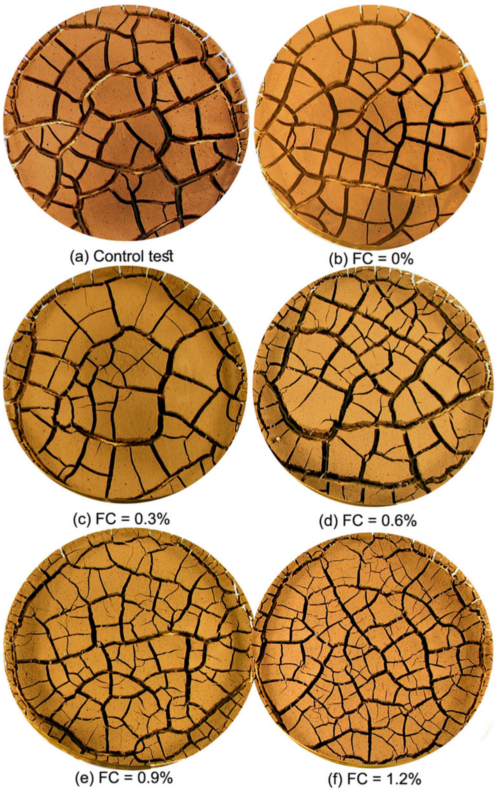

(a) Control test
(b) FC = 0%
(c) FC = 0.3%
(d) FC = 0.6%
(e) FC = 0.9%
(f) FC = 1.2%

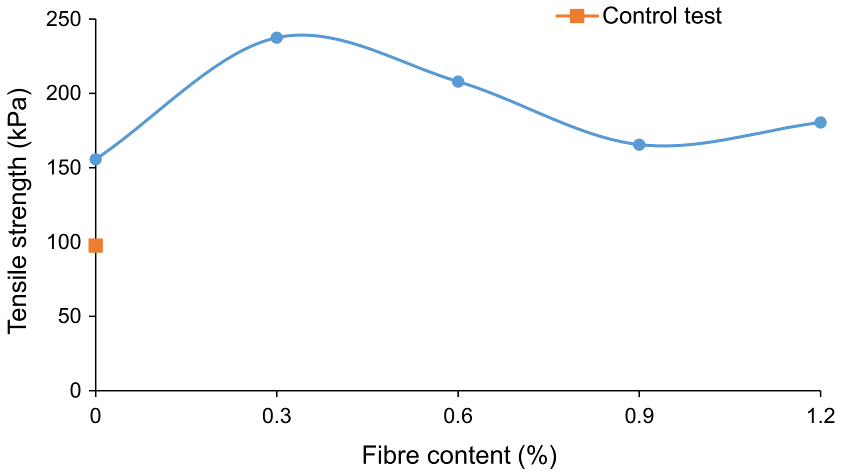
Fig. 4 Clay crack patterns for different fibre contents (f_c) at the end of drying

Tensile strength

Results of tensile strength test, as shown in Fig. 5, disclose a substantial tensile strength gain. The specimen with enzyme only (f_c = 0%) also possessed more tensile strength than the plain Merri-Creek clay. Hence, it can be stated that addition of both enzyme and fibre enhances tensile strength of clay. The reinforcing effect of fibre on tensile strength is consistent with literature such as Harianto et al. (2008b). The increase in tensile strength, however, does not grow continuously with the fibre content. Accordingly, Fig. 5 suggests 0.3% as the optimum fibre content for maximum tensile strength. The additional strength gained from fibre addition depends mainly on the adhesion between the fibre and soil. At higher fibre contents, fibres tend to form clusters among themselves therefore limiting the adhesive effect between soil and fibre. The drop in tensile strength beyond f_c = 0.3% can be attributed to this clustering effect which results in slippage based on visual observations.

Dry density of treated compacted clay was determined from the beams used for tensile testing at the same moisture

Fig. 5 Variation of tensile strength with fibre content



content of 30%. Figure 6 depicts variations in dry density with changes in fibre content. It should be noted that these are not the maximum dry densities of treated clay. However, they should not be far from maximum dry density since their compacting moisture content is close to the optimum. As explained earlier, enzymes work on the soil lattice to densify the soil when acting alone. Renjith et al. (2020) identified the basic mechanism of enzymatic action as densification through both macroscopic and microscopic analysis. Hence, the increase in dry density can be partially attributed to enzymes. Fibre addition also causes an initial increase in dry density by helping soil particles re-arrange in a dense structure. Moreover, fibres can fill some of the voids between soil particles. When the fibre content is high, fibres replace soil particles. As the specific gravity of fibre is less than that of soil, this results in a decrease in dry density. Thus, the peak behaviour in dry density can be attributed to the inclusion of fibre. Similar trends can be seen in the results presented by Harianto et al. (2008b). From Fig. 6, it is clear that both enzyme and fibre improve dry density and suggest an optimum fibre content between 0.3 and 0.6% for maximising dry density.

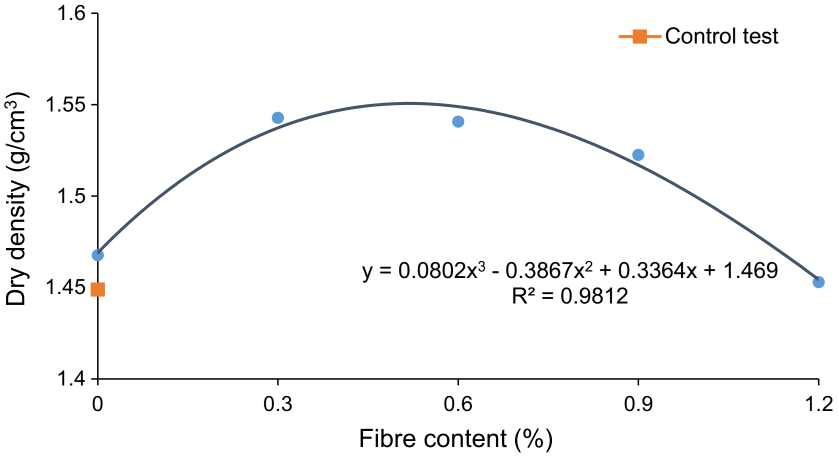
Discussion

Crack initiation

Crack initiation is an important consideration in desiccation crack analysis. It is generally accepted that a crack is initiated as a result of tensile failure. Under restrained boundary conditions, shrinkage induced by the loss of moisture generates tensile stresses within the soil mass. When the generated tensile stress exceeds the tensile strength, material fails opening up a crack. The alternative approach to analyse desiccation cracks is using strain energy dissipation in fracture mechanics. Soil mass stores strain energy during shrinkage. When there is sufficient energy to create two new surfaces, a crack is formed. However, in linear elastic fracture mechanics (LEFM) theory, the existence of a small crack is presumed. Therefore, LEFM is more suitable for explaining the subsequent propagation of a crack while the initiation of it can be described using the strength criterion.

At the onset of cracking in a uniform material, the failure is most likely to take place at the top surface where the tensile stresses are maximum (Kodikara and Choi 2006). In reality,

Fig. 6 Variation in dry density at various fibre contents



the spatial variation of tensile strength may not be uniform due to material non-homogeneity and the presence of flaws. Costa et al. (2013) illustrated how a crack can be initiated through a flaw (e.g. an air bubble or a weak plane) at a point away from the location of maximum tensile stress. It can be speculated that fibre acts as flaws or weak planes (the interface between fibre and soil) triggering crack initiation all over the specimen. This explains the messy, non-orthogonal crack patterns in fibre-treated soil. Wang et al. (2018) showed evidence of cracks starting from the bottom surface of the specimen even with no fibre in soil. The presence of fibre in subject experiments can certainly increase this tendency.

In unsaturated soil mechanics, tensile stress is developed by matric suction which in turn is related to the water content. Figure 7 shows the cracking water content ($\boldsymbol{w}_{\mathbf{cr}}$ = water content at crack initiation) for different fibre contents. Studies by Corte and Higashi (1964) and Nahlawi and Kodikara (2006) have established that the $\boldsymbol{w}_{\mathbf{cr}}$ is a function of specimen thickness and the drying rate. In general, thicker specimens and lower drying rates are associated with low $\boldsymbol{w}_{\mathbf{cr}}$. However, neither thickness nor drying rate has been varied in current tests. Thus, the decreasing trend in cracking water content may be attributed to the addition of fibre content. The comparison between the control test and test with no fibre ($\boldsymbol{f}_{\mathbf{c}}$ = 0%), however, suggests that the enzyme is responsible for increasing the $\boldsymbol{w}_{\mathbf{cr}}$ (Fig. 7). Under constant enzyme content, specimen thickness and drying rate, the relationship between $\boldsymbol{w}_{\mathbf{cr}}$ and fibre content ($\boldsymbol{f}_{\mathbf{c}}$) can be presented in the following form (Fig. 7):

$$w_{cr}{=}{-}Af_{\mathrm{c}}+B \qquad (1)$$

where $\boldsymbol{A}$ and $\boldsymbol{B}$ are constants (> 0). However, given the moderate R^2 value (0.6184) of this relationship, it should only be taken indicative of the downward trend. The establishment of a more reliable linear relationship between $\boldsymbol{f}_{\mathbf{c}}$ and $\boldsymbol{w}_{\mathbf{cr}}$ will be possible by using fibre as the only additive.

As noted above, crack initiation occurs due to the tensile failure. Inclusion of fibre imparts additional tensile strength to clay. A simple explanation, therefore, for the reduction in $\boldsymbol{w}_{\mathbf{cr}}$ can be the additional reinforcement provided by fibre. This requires the clay layer to dry further and develop more tensile stresses to overcome the increased tensile strength.

Crack intensity

One of the key undesirable effects of desiccation cracks is the promotion of hydraulic conductivity. As discussed earlier, this can severely undermine the performance of clay infrastructure acting as hydraulic barriers. Generally, the first feature of the extent of desiccation cracks captured by visual observation is the number of cracks. As seen in Fig. 4, fibre and enzyme-treated clay produced more cracks than plain Merri-Creek clay. However, the effect of cracking cannot be quantified solely on the basis of number cracks. The width and the depth of cracks also need to be considered to understand the complete effect. The depth of the cracks in the subject study specimens can be taken to be equal since all the cracks penetrated full depth. The width of the cracks can be accounted by determining the crack intensity factor (CIF) which is defined as (Miller et al. 1998),

$$\mathrm{CIF} = \frac{\text{area of cracks}}{\text{total area}} \times 100 \qquad (2)$$

The change of CIF with additives is shown in Fig. 8 and highlights that the additives used are capable of reducing the CIF. When comparing the plain Merri-Creek clay specimen and the specimen with f_c= 0%, it can be seen that enzyme alone can bring the CIF down considerably. The addition of fibre can further lower the CIF. An optimum fibre content with respect to lowest CIF can be obtained from Fig. 8 between 0.3

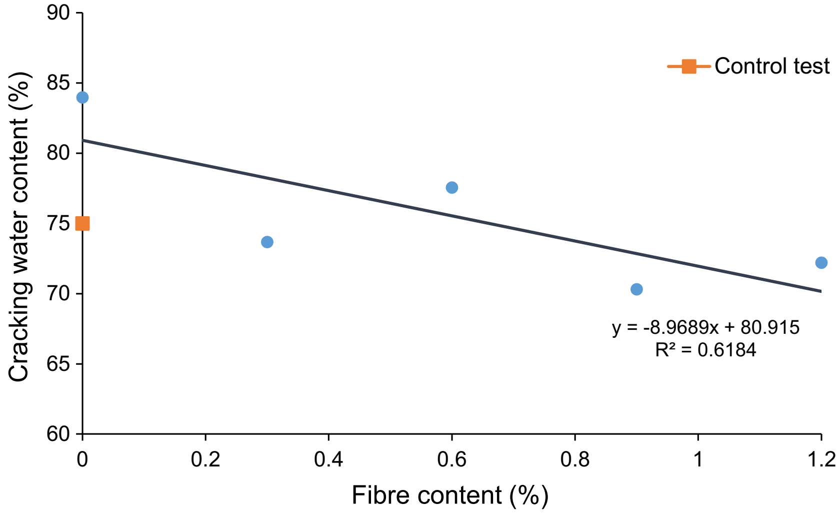
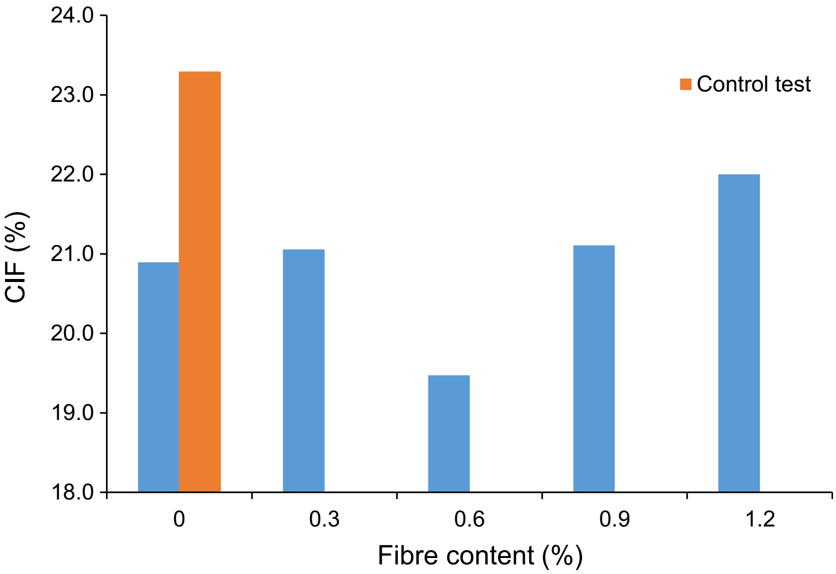


Fig. 7 Change in cracking water content with fibre content

Fig. 8 Changes in crack intensity factor (CIF) with fibre addition



and 0.6%. This is further strengthened by the crack reduction ratio (R_{cr}) shown in Fig. 9. The ratio, R_{cr}, of treated specimens was calculated corresponding to the total crack area of the control specimen as described in Tang et al. (2016b). This ratio showed a constantly increasing trend in the desiccation cracking tests presented by Tang et al. (2016b) where fibre was the only additive. The presence of enzymes in the current study creates a peak behaviour in R_{cr} suggesting an optimum additive content around $f_c = 0.6\%$.

A lower CIF in fibre-treated specimens can be interpreted as the availability of larger uncracked area regardless of having a higher number of cracks. This means (as can also be seen visually in Fig. 4) the cracks are shorter and narrower. This is an advantage under field conditions since there is the possibility of self-healing of narrower cracks when they go through natural wet-dry cycles.

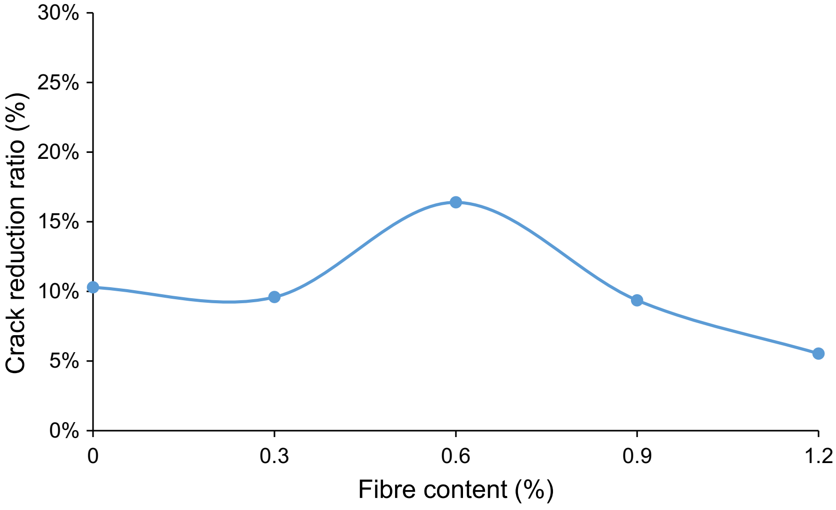
Effects of additives on tensile strength

Clay soil has only a nominal tensile strength. An additional tensile support to clay is beneficial in geotechnical applications including mitigation of desiccation cracks. As noted above, the ability of fibre to add tensile strength to soil is well established (Harianto et al. 2008b; Ziegler et al. 1998). The additional strength provided by fibre or the strength gain in reinforced clay is attributed to pullout resistance, which depends on the interface friction and adhesion between the fibre and soil (Koerner 1994). Strength gain, ΔT_{fibre}, due to fibre addition can be expressed in the following form (Koerner 1994).

$$\Delta T_{\text{fibre}} = C_a + \sigma_{n,f} \tan\delta \tag{3}$$

where C_a is the adhesion of fibre to soil, $\sigma_{n,\ f}$ is the normal stresses acting on fibre and δ is the friction angle between fibre

Fig. 9 Crack reduction ratio



and soil. The friction between the fibre and soil depends on soil type, density and water content. However, if measured under the same water content for a given soil, fibre and compaction energy, $\Delta T_{\mathrm{fibre}}$ should be a function of fibre content only as the amount of support provided depends on the number of fibres across a crack plane.

Figure 10 shows the experimental data available in literature for the tensile strength gain as a percentage of unreinforced tensile strength with varying fibre content. These experiments used different methods, soils and fibre. Nevertheless, a linear relationship can be found between $\Delta T_{\mathrm{fibre}}$ and fibre content in all data sets. Rifai and Miller (2009) developed a theoretical model for $\Delta T_{\mathrm{fibre}}$ starting from Koerner's expression in Eq. 3. The model is applicable to unsaturated soils and is a function of water content. Under a specific water content for a given soil, fibre and compaction energy, the model can predict $\Delta T_{\mathrm{fibre}}$ at different fibre contents. Such predictions for a hypothetical soil (Rifai and Miller 2009) are also included in Fig. 10. The model agrees with the linear relationship between $\Delta T_{\mathrm{fibre}}$ and fibre content depicted by experimental results.

Based on the data presented in Fig. 10, it can be postulated that the additional tensile strength added by fibre will increase linearly with fibre content. However, the results of the subject study (also shown in Fig. 10) do not follow the linear relationship described above. A possible reason for this could be the influence of enzyme. The enzyme contributes to the increase in tensile strength when acting alone in clay (Fig. 5). It is suspected that the deviation of current results from the linear behaviour of other data in Fig. 9 is caused by the interaction between enzyme and fibre.

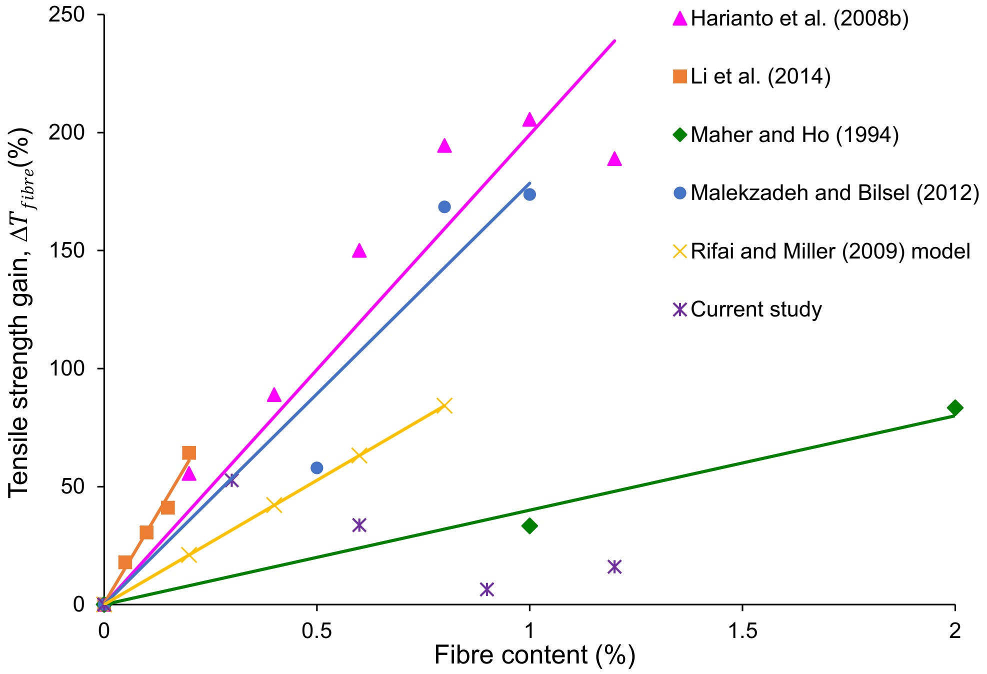
Nylons are polyamides that contain carbonyl and amine groups (Kim and Palomino 2009). Similar to other polyamides such as proteins, nylons are also susceptible to enzymatic catalysis. According to Parvinzadeh et al. (2009), enzymatic hydrolysis of nylon fibre changes properties such as hydrophobicity and build-up of electrostatic charge. Using a Fourier transform infrared spectroscopy (FTIR) analysis, Gashti et al. (2013) showed that two of the active enzymes in Eko-Soil, lipase and protease, react with nylon and change properties such as drapeability. This is strong evidence to suggest that there is interaction between nylon fibre and Eko-Soil. Moreover, it explains the reason for the random behaviour of tensile strength gain in the subject study (Fig. 9).

However, the underlying behaviour of this enzyme-based product in the presence of a synthetic fibre cannot be described conclusively based on the tests carried out in this study. Molecular level investigations are needed to fully specify the effect of enzymes on nylon fibre. Nonetheless, looking at the results, it is apparent that the addition of enzyme-containing product reduces the intensity of desiccation cracking (see comparison with control test in Fig. 5). Regardless of the characteristics of each component, the findings indicate that a combination of the enzyme components improves tensile strength properties of the soil and thus mitigate desiccation cracking effectively.

Conclusions

Laboratory experiments were conducted to study the combined effects of the addition of nylon fibre and an enzyme-

Fig. 10 Variation of tensile strength gain with fibre content



containing product on crack initiation in clay, cracking water content, extent of cracking and tensile strength.

The selected additives were able to mitigate the extent of cracking. Considerable changes were seen in crack patterns of amended clay. As the fibre content increased, the cracks became less elongated and the amended specimens produced more cracks than the control specimens. More significantly, however, the crack intensity factor decreased with the increasing additive dosage.

Fibre and enzyme are capable of delaying the crack initiation. For a given specimen thickness (10 mm in these experiments) and drying rate, cracking water content decreased as the fibre content increased, exhibiting a near linear relationship between the two parameters. The addition of fibre enhanced the tensile resistance of soil requiring the specimen to dry further to build sufficient tensile stresses to open cracks.

Both fibre and the enzyme provided additional tensile resistance to compacted clay. According to published literature, the strength gain is linearly proportional to the fibre content at a given water content for soils reinforced with fibre. However, this relationship was not evident in the present study despite having gained a substantial strength increment. It is believed that the chemical reactions between fibre and enzyme obscured the individual actions.

The influence of fibre was noticeable in association with the reported work in literature. The comparison between control tests and tests with no fibre in the present study allowed the effect of enzymes to be discovered. However, extent of enzyme influence was not explicit and therefore further macro and micro-scale investigations are needed to understand the enzymatic action. It should also be noted that the same amount of enzyme-based product was applied in all the tests. Tests with varied quantities of enzymes will reveal the full usefulness of it.

Considering the results for dry density, tensile strength and CIF, a fibre content between 0.3 to 0.6% can be recommended to obtain optimum outcomes. However, it should be noted that this percentage is valid only for thin soil layers around 10 mm and depends on fibre type, length and diameter, soil type and drying rate. The impact on hydraulic conductivity also needs to be studied for relevant applications. The scope of future research will be to further explore these dependencies.

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