

EFFECTS OF FIBRES ON DEVELOPMENT OF CRACKS IN CLAY

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ABSTRACT

This paper presents the results of laboratory tests on samples of clay reinforced with different amounts of synthetic fibres. The main objective of the paper is to investigate the effects of synthetic fibres on controlling desiccation cracking in clays. Samples of clay were compacted in thin layers with different fibre contents and tested for shrinkage cracking. Samples of reinforced clay were also used for index and strength tests. The results of the tests show that increasing fibre content reduces the density, the width and the length of cracks. Unconfined compressive tests and Brazilian tensile splitting tests indicate that by increasing fibre content both compressive and tensile strengths of the clay increase. However, the increase in tensile strength is considerably greater than the increase in compressive strength. Visual observations and image processing of the crack densities of samples show that by an addition of 3-4% fibre, by weight, into the clay, desiccation cracking can be fully controlled.

1 INTRODUCTION

Clay is the most common material used in the construction of flexible hydraulic barriers, in landfills, earthfill dams, impermeable cutoff walls etc., due to its low permeability. However, the permeability of clay increases significantly if desiccation cracking occurs. The extent and rate of cracking is dependent on various factors such as the moisture content, density, temperature and plasticity of the soil, as well as the confining pressures applied to the soil. Cracks and fissures in clay create pathways that facilitate seepage and flow of fluids and can significantly affect the permeability of the soil. To overcome this problem several techniques such as addition of lime, cement and fibres have been proposed, many of which are routine methods of improving the strength and stiffness of clays. Inclusion of natural fibres in clay to control shrinkage cracking has been practiced by many civilizations in the Middle East (Figure 1), where short wheat straws were used as reinforcing elements in clay plasters. Past experience has also shown that inclusion of fibres can improve shrinkage characteristics of clays.

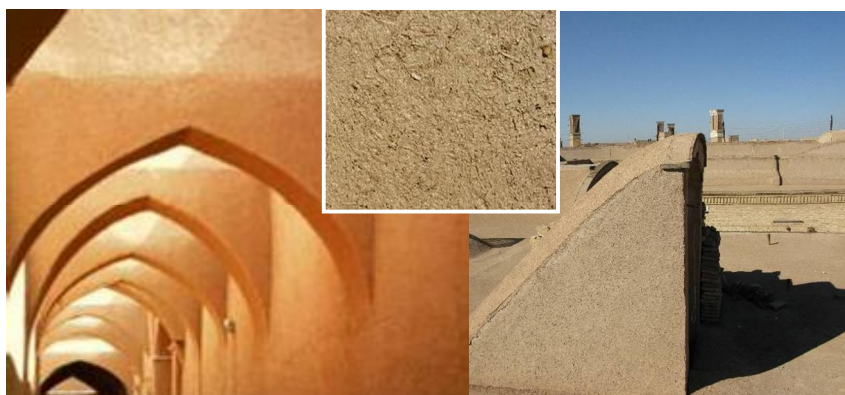


Figure 1: Fibre reinforced clay plaster on walls and roofs (Yazd, Iran).

In recent years many attempts have been made to use synthetic fibres for reinforcement of cohesive and cohesionless soils to increase their strength and load bearing capacity. The ability of plant roots to increase the shearing strength of soils in natural slopes has been reported among others by Gray (1970), Waldorn (1977) and Wu *et al.* (1998). Application of synthetic fibres in geotechnical engineering projects was introduced in the late 1980s after initial studies were conducted on the mechanical behaviour of reinforced soils. In the past 25 years most of the investigations on fibre reinforced soils were concentrated on granular materials (Gray and Ohashi, 1983; Maher and Gray, 1990; Al-Refeai, 1991 and more recently Ibraim *et al.*, 2006 and Diambra *et al.*, 2007). There has also been limited research on the application of synthetic fibres for reinforcement of cohesive soils. Andersland and Khattack (1979) investigated the

effects of cellulose pulp fibre inclusion on shear strength and stress-strain behaviour of kaolinite clay. They found that the inclusion of fibres increases the peak shear strength of the soil under all testing conditions (UU, CU and CD) and also increases the ductility of the material. Maher and Ho (1994) found that randomly distributed fibres increase the ductility, peak unconfined compressive strength, tensile splitting strength and flexural toughness of kaolinite clay. They also found that the hydraulic conductivity of the fibre reinforced clay increases by increasing the fibre content. Limited attempts have also been made to control clay cracking by fibre reinforcement (Allan and Kukacka, 1995; Al Wahab and El-Kedrah, 1995; Ziegler *et al.*, 1998). Miller and Rifai (2004) studied the effects of fibre reinforcement on the development of desiccation cracking in compacted clay samples. They found that an addition of 0.4-0.5% fibre can reduce the crack density by 50% while the hydraulic conductivity remains in the acceptable range.

Miller *et al.* (1998) proposed a similar definition for crack intensity. A crack intensity factor (CIF) was defined as the ratio of the area of the cracks to the total surface area of a drying soil mass. These areas were determined using photographs of the surface of desiccated soils and a computer aided image analysis program. Cracks appear darker than the remaining uncracked soil surface in photographs of a desiccated soil.

Measurement of crack density has been usually performed on small diameter and relatively thick samples of soils. During shrinkage a large portion of volume change occurs due to the shrinkage of samples from their boundaries. Therefore any measurement of desiccation cracking will be a qualitative measure rather than a quantitative one. The behaviour of these samples does not represent the real behaviour of clay liners. The clay liners in the field are spread over a large area in a relatively thin layer of 300 mm to 500 mm thick. The extent of the soil boundaries prevents sliding of the liners over the underlying layer and therefore generates additional horizontal tensile stresses in the soil during shrinkage. These stresses increase the area of the cracks in the clay liners, as compared to the crack area formed in soil samples with a limited horizontal dimension. Examples of boundary shrinkage in samples of soil with and without fibre are reproduced from Miller and Rifai (2004) and presented in Figure 2. It is clear that the crack density in these samples is influenced by the shrinkage of their boundaries and the dimension of the samples. The reduction of desiccation cracking due to inclusion of fibres in small samples of clay is significantly larger than that which could occur in the field conditions.

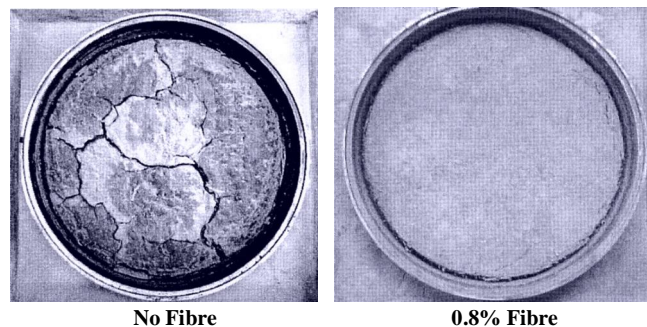


Figure 2: Boundary shrinkage of soil samples (reproduced from Miller and Rifai, 2004).

In this paper a method is presented that can be used to eliminate the effects of boundary shrinkage on desiccation cracking of samples of clays. A thin layer of clay, with or without fibres, is compacted on fully rough surfaces over a relatively wide area to simulate the conditions of clay liners in the field. The rough surface prevents the soil sample from sliding in the two horizontal directions, thereby simulating the boundary conditions of the clay liners in the field.

The main objective of the experimental work in this study is to investigate the effectiveness of fibre inclusions in controlling the shrinkage cracking under extreme temperature and moisture conditions. In addition, the results of limited index tests and strength tests are also presented.

2 TESTING MATERIALS

2.1 SOIL TYPE

The soil used in this study is a commercially available kaolinite with trade name Q145. The basic mineral compositions and the physical properties of the clay, provided by the manufacturer, are listed in Table 1. The results of Atterberg limits, linear shrinkage and compaction tests on samples of the soil are summarised in Table 2. The grain size

distribution of the soil is shown in Figure 3, which indicates that the soil is a mixture of silt and clay. The soil has a plastic limit of 33%, plasticity index of 10%, and linear shrinkage of 3.8%. It has about 40% clay particles and is classified, based on Unified Soil Classification System as low plasticity clay, CL.

Table 1 Mineral composition and physical properties of Q145 clay Table 2 Summary of the index and compaction tests

Silica	SiO ₂	49.3 %
Alumina	Al ₂ O ₃	33.8 %
Potash	K ₂ O	2.4 %
Titania	TiO ₂	1.5 %
Ferric Oxides	Fe ₂ O ₃	0.8 %
Magnesia	MgO	0.4 %
Others	Na ₂ O, CaO, etc.	11.8 %
Specific Gravity	-	2.69
Surface Area	m ² /g	12.9

Plastic Limit	33%
Plasticity Index	10%
USCS	CL
Linear Shrinkage	3.8%
Maximum Dry Density*	15.5 kN/m ³
Optimum Moisture Content*	25%

* Determined using Proctor test

2.2 FIBRE TYPE

The fibre used in this study is Homopolymer Polypropylene, which is commonly used in reinforcing concrete and soil. The fibre has high chemical resistance, low electrical and thermal conductivity, and nil water absorption, with a specific gravity of 0.91. It has a high melting point of 162°C, which makes it possible to place the fibre mixed soil in the oven. The length of the fibres varies between 20 mm to 25 mm. It is produced in fibrillated bundles, but the mixing procedure opens the bundles and separates them into bundles of filament fibres with an average diameter less than 0.1 mm (Figure 4).

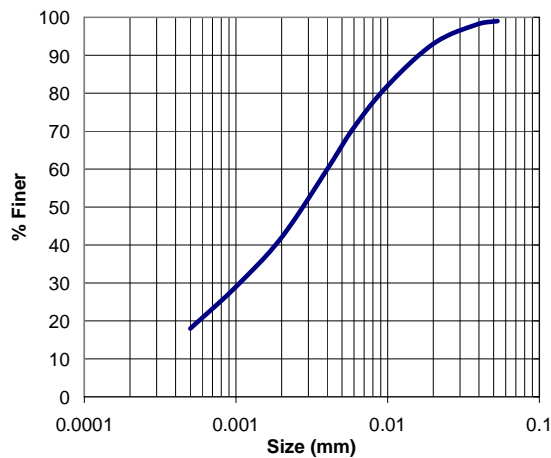


Figure 3: Grain size distribution of Q145 clay.



Figure 4: Homopolymer Polypropylene fibre.

3 STRENGTH TESTS

The compressive and tensile strengths of samples were obtained using both unreinforced clay and fibre reinforced clay. Reinforced samples were prepared by mixing the clay with 1% and 2% (by weight) of the fibre. Cylindrical samples with 100 mm diameter and 200 mm height were used to find the unconfined compressive strength and the tensile strength using Brazilian splitting test.

Dry clay powder, water and fibres were mixed by hand to achieve maximum homogeneity in the mixture. The cylindrical samples were prepared at optimum moisture content using static compaction to achieve the maximum dry density. To investigate the effects of moisture content on strength, “moist” and “dry” samples of the soil were prepared. The moist samples of clay were cured for 3 days at its optimum moisture content. The “dry” samples were prepared by keeping the soil in the oven for 24 hours at 50°C temperature.

The results of compressive and tensile splitting tests of different samples are presented in Figures 5 and 6. These figures show the effects of fibre content and moisture content on the strength of the samples. In general, as expected the strengths of dry samples are greater than the strengths of samples at their optimum moisture content. The ductility of dry samples under compressive stress is less than that of moist samples. Inclusion of fibres increases both compressive and tensile strengths of the reinforced soil. While the increase in compressive strength is not significant, inclusion of 1% fibre increases the tensile strength of the clay by about 75%. Fibres also increase the ductility of the soil mixes both in compressive strength and tensile strength tests. More importantly, the post peak strength loss is reduced considerably for fibre reinforced samples in the splitting tensile strength tests.

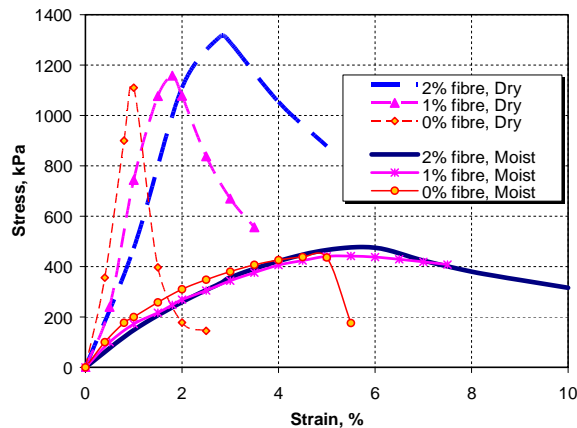


Figure 5. Unconfined compressive strength of samples.

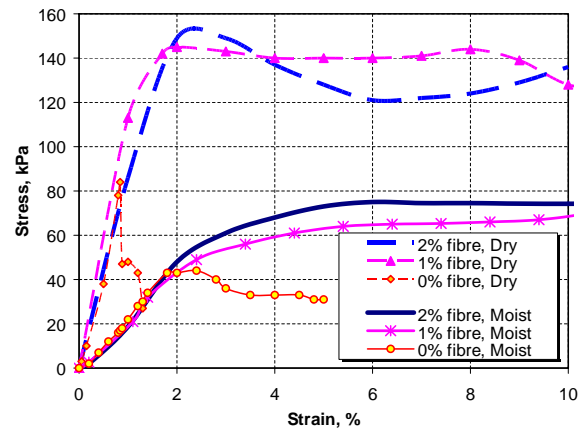


Figure 6: Tensile strength of samples.

4 LINEAR SHRINKAGE TEST

In order to evaluate the potential of synthetic fibres in controlling shrinkage cracking, a series of linear shrinkage tests were carried out using 500 mm long, 25 mm diameter, semi-cylindrical moulds. Samples of clay with moisture content equal to the plastic limit of the soil were mixed with 0 to 2% fibre (by weight) and packed in the mould. Figure 7 shows images of the samples after they were oven dried for 24 hours. The number of major and minor cracks and the percentage of linear shrinkage for each sample are given in Table 3. Major cracks are defined as those which have a width of at least 0.4 mm and cross the whole section of the sample, while minor cracks pass through part of the section. It can be seen that an addition of 1% fibre considerably reduces the linear shrinkage potential of the clay and eliminates shrinkage cracks of the reinforced sample, although the sample still exhibits shrinkage. Figure 8 shows the variation of linear shrinkage versus fibre content. An addition of 2% fibre reduces the linear shrinkage to about 5% of the linear shrinkage observed in the sample with no fibre.

5 CRACK DENSITY TESTS

This set of the tests was designed to evaluate the effects of fibre inclusion on shrinkage cracking that occurs during extreme moisture content changes. To simulate the boundary conditions of a relatively thin clay liner covering a large area, samples of soil were prepared as 305 mm × 305 mm tiles, with a thickness (after compaction) of 12 mm ± 1 mm. Initial experiments showed that if the clay is cast on the surface of a smooth plate the clay slides over the plate during drying process and no substantial crack will be formed. To prevent sliding and to model the boundary conditions of clay liners in the field a thin steel mesh was attached onto a wooden plate and the soil samples were cast on the mesh and the wooden base plate. The mesh has a thickness of 0.7 mm with 12.5 mm × 12.5 mm opening dimensions. Figure 9 shows the casting mould and the wooden base plate with the steel mesh.

Several samples were prepared using 0%, 0.5%, 1%, 1.5%, 2%, 3% and 4% fibre contents. To generate a greater potential for development of shrinkage cracks, the moisture content of the samples was selected to be 39.6%, which is 20% more than the plastic limit of the soil. The samples were subjected to a static compaction pressure of 300 kPa to achieve a thickness corresponding to the saturated density of the clay. After compaction, all samples were kept for 24 hours in the oven at 105°C for 24 hours.

Table 3: Behaviour of samples in linear shrinkage bar.

Fibre content (%)	No. of major cracks	No of minor cracks	Linear shrinkage, (%)
0.0	5	0	3.8
0.3	1	7	2.0
0.6	0	1	1.4
1.0	0	0	0.9
1.5	0	0	0.2
2.0	0	0	0.2

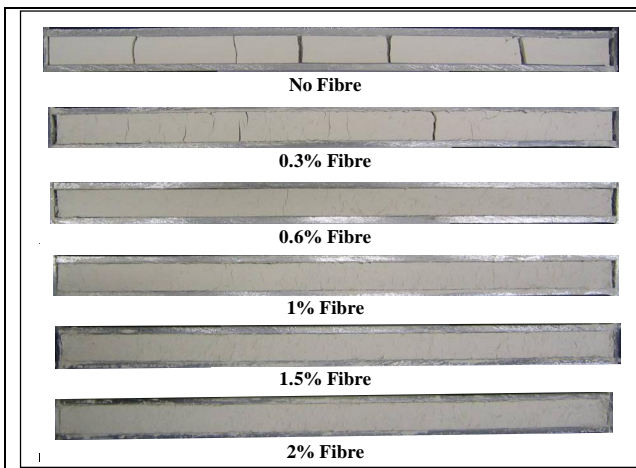


Figure 7: Images of reinforced clay samples after drying in linear shrinkage moulds.

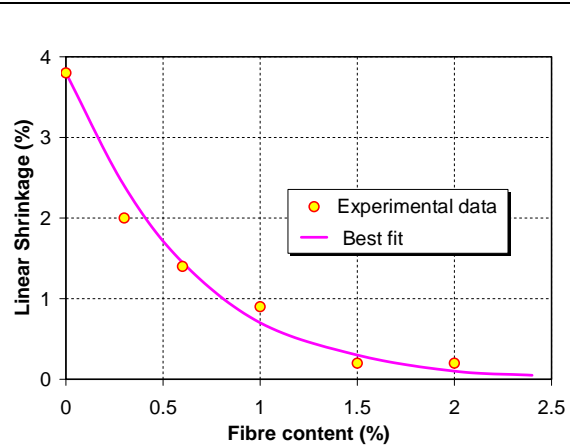


Figure 8: Variation of linear shrinkage with fibre content



Figure 9: Casting mould and wooden plate covered by steel mesh.

Images of the oven dried samples were taken for crack density analysis. The surface of the clay samples was uniformly illuminated by four sources of light and surficial images of the samples were taken by a digital camera.

The crack density in each sample was obtained as the ratio of the total area of the cracks, A_c , to the total surficial area of the samples, A . The area of the cracks was determined by counting the number of dark pixels in the surficial image of the clay tile. This requires setting a grey threshold; any darker pixel is assumed to be within a crack. To find the grey threshold, various trials were carried out and the detected cracks were plotted and compared with the actual crack pattern observed on the surface of each sample and then the best threshold was selected. It was noted that the grey threshold

remains unchanged, regardless of the fibre content of the samples, for a given light intensity used to illuminate the samples. The grey threshold for the present work was set to 127. A microscopic study of the crack patterns reveals that the image processing with this grey threshold has detected cracks with a minimum width of 0.2 mm. Inclusion of some dark pixels corresponding to the exposed fibres and their shadows as parts of crack is also inevitable, but its overall effect on the crack intensity was found to be insignificant. Cracks thinner than 0.2 mm could have been detected if a lower grey threshold had been selected in the image processing, but more extra pixels corresponding to the exposed fibres would have also been included as cracks which artificially increase the total area of the cracks.

Figure 10 shows images of clay tiles with different fibre contents and the crack patterns detected by the image processing. The detected cracks match well with the actual crack patterns.

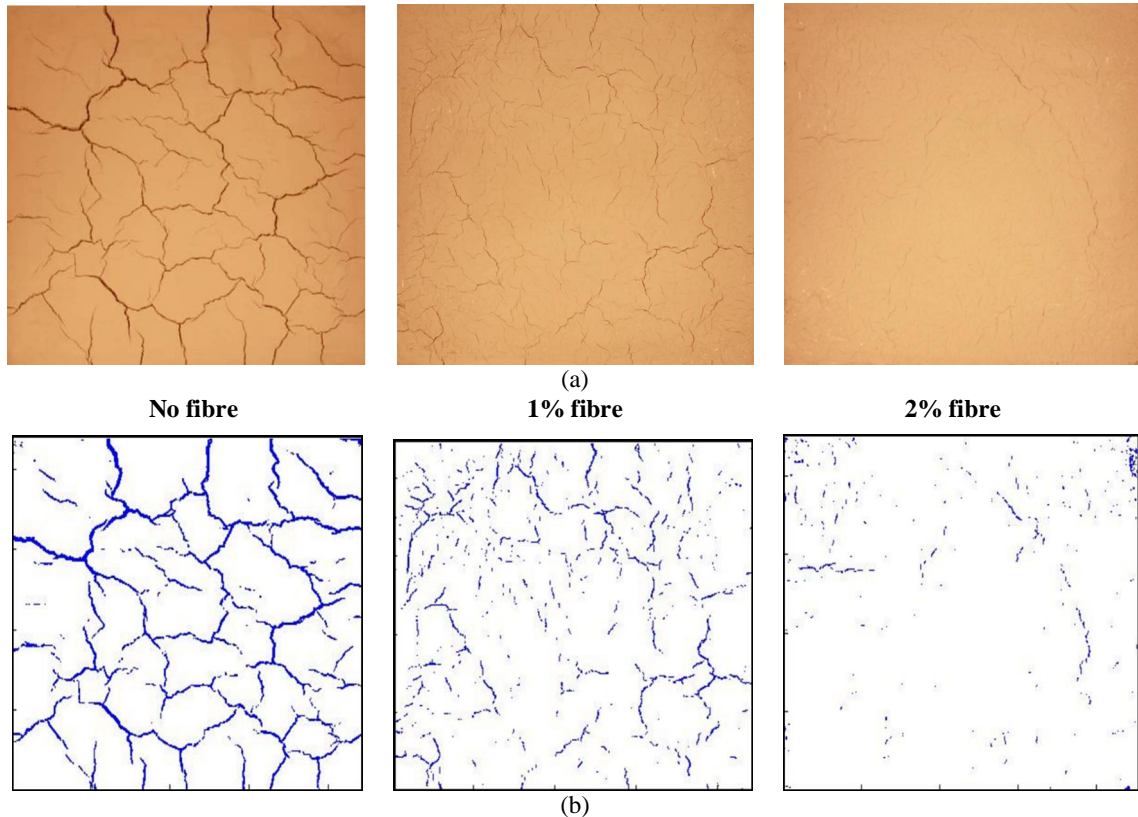


Figure 10: Actual crack patterns (a) and detected crack patterns (b) of samples with different fibre contents

As mentioned previously, a crack intensity factor (CIF) can be defined as the ratio of the area of the cracks to the total surface area of the sample, A_c/A . To present the relative effectiveness of fibre inclusions on reducing the crack density, a crack reduction factor (CRF) can be defined as (Miller and Rifai, 2004):

$$CRF = \frac{CIF_n - CIF_f}{CIF_n} \times 100$$

where CIF_n is the crack intensity factor of samples of natural soil with no fibre and CIF_f is the crack intensity factor of samples reinforced with fibre. For a sample with no fibre CRF is zero. When all cracks are eliminated CIF_f is zero and CRF will be 100%.

The variations of CIF and CRF versus fibre content are given in Table 4 and also presented in Figure 11. The results of the tests show that a fibre content of about 2% eliminates 95% of the shrinkage cracks wider than 0.2 mm.

The effect of sample thickness on crack density was also investigated. Samples of unreinforced clay with thicknesses ranging from 12 mm to 16 mm were prepared and tested for crack density after oven drying. The crack intensity factor, CIF, of each sample was then evaluated. The results showed that the crack intensity factors for these samples remain practically constant, with values between 2.93% and 2.96%. However, the width and the spacing of the cracks increase slightly as the thickness of the sample increases. This indicates that the horizontal shrinkage of the top surface

boundaries of these samples is still insignificant. If the thickness of the samples is increased further, there will be shrinkage at the top surface boundaries which reduces the crack intensity factor.

Table 4: Variation of CIF and CRF.

Fibre Content (%)	CIF	CRF
0.0	2.97	00.0
0.5	1.26	57.6
1.0	0.52	82.5
1.5	0.33	88.9
2.0	0.13	95.6
3.0	0.07	97.6
4.0	0.02	99.3

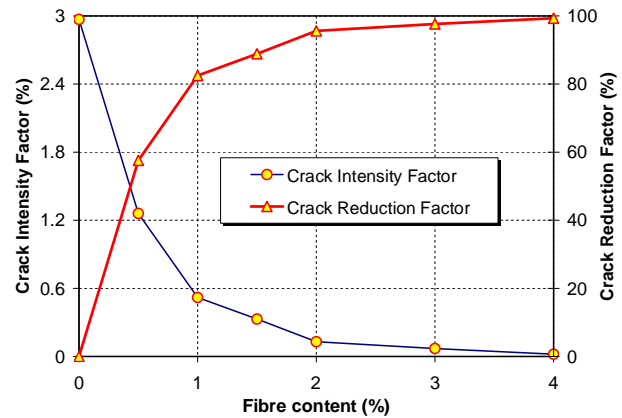


Figure 11: Variation of CIF and CRF with fibre content.

6 CONCLUSIONS

The results of a series of laboratory tests on samples of clay reinforced with different amounts of fibre are presented. Fibre inclusion increases the ultimate tensile strengths of the clay, as measured in Brazilian splitting tests. The tensile strength increases by 75% with inclusion of only 1% of fibre. Fibre inclusion also increases the ductility and reduces the post peak strength loss of the clay under tension. The results of unconfined compressive tests on moist and dry samples indicate that inclusion of fibre does not have a significant effect on the ultimate compressive strength of the clay. However, it has a pronounced effect on increasing the ductility of the clay samples under compression.

Linear shrinkage tests show that inclusion of only 2% fibre can reduce the linear shrinkage of the clay, prepared at its plastic limit, from 3.8% to 0.2% or practically eliminates the cracks.

Thin samples of clay with dimensions of 305 mm × 305 mm × 12 mm were prepared with different fibre contents at a moisture content 20% higher than the plastic limit of the clay. Visual observation and image processing of the developed cracks show that inclusion of 1% fibre reduces the crack density from 3% to 0.5%. The cracks are practically eliminated by inclusion of 3% fibre.

Reduction of crack density and crack width maintains the low permeability of clay and prevents dispersion of the desiccated soil particles when subjected to a flow of water. This in turn prevents deterioration of the soil impermeability during cycles of wetting and drying.

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