Stabilization of clayey soil using fibre reinforcement

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ABSTRACT: The paper presents experimental and numerical investigations on crack evolution during desiccation, on unsaturated, compacted and reinforced clay using natural Alfa fibres. The effect of fibre content is investigated and a comparison between experimental and numerical simulations is made. A modified model for tensile strength is updated in the finite element program CODE_BRIGHT and used to predict tensile cracks induced by desiccation on reinforced soil. The results show that the soil desiccation cracking behaviour is significantly influenced by fibre inclusion and that experimental and numerical results are in good agreement.

1 INTRODUCTION

The behaviour of soils submitted to desiccation conditions can be affected by many factors such as stress history, temperature, time effects, tensile strength, depth and intrinsic permeability. Examples can be found in irrigated land, tailing ponds for mining waste, landfill liners, earth embankments, reclaimed land, reservoir beds, etc. Physical properties and the behaviour of cracked soils are quite different from those of the intact soil. Hydraulic conductivity increases due to crack formation which has several adverse effects in different situations, such as rapid and direct movement of water and solutes from the soil surface to the depth. Recently, there is a renewed interest of using fibre additive to overcome the desiccation cracking problem (Al Wahab and El-Kedrah 1995; Ziegler et al. 1998; Miller and Rifai 2004; Harianto et al. 2008). Al-Wahab and El-Kedrah (1995) reported a reduction of 25%–45% in desiccation crack index (ratio of area of cracks to the total surface area) due to fibre reinforcement of compacted clay. The amount of shrinkage was also reduced by 30%–35%. Ziegler et al. (1998); Miller and Rifai (2004) and Harianto et al. (2008) also observed that fibre inclusion reduces the desiccation cracking of the soil, along with an improvement in the mechanical performance of the soil.

However, compared with the results on mechanical behaviour, information related to the desiccation cracking behaviour of fibre-reinforced soil is relatively limited. More quantitative studies are necessary for further understanding of crack initiation and propagation characteristics of fibre-reinforced soil.

In the present paper, experimental and modelling investigations were carried out to study the effect of fibre reinforcement on preventing desiccation cracks in compacted clay. A new model that relates the porosity evolution and the suction to the tensile strength, considering the effect of fibre reinforcement, was developed and implemented in the finite element program CODE_BRIGHT. The proposed model captured the initiation and propagation of cracks in a thin layer of desiccated clay and predicted crack patterns in terms of crack intensity factor. Natural Alfa fibres were used as an additive material for clayey soil. The percentages of fibre used η_f were varied as 0.0% and 0.3% (by dry mass of soil). The soil specimens were compacted under the conditions of maximum dry density and optimum water content. The desiccation crack test results indicated that using natural Alfa fibres was significantly effective on restraining crack propagation in compacted soil. Moreover, the new developed model was found able to reproduce experimental results and to predict the crack propagation in the fibre reinforced soil.

2 MATERIALS AND METHODS

2.1 *Soil properties*

The test was performed on a clayey soil. Table 1 summarizes the main properties. The soil was passed through a mechanical sieve (size 0.4 mm). The dry sieved material was then mixed with distilled water until a visibly homogeneous paste was obtained.
The relationship between the suction and degree of saturation has a very important role in the characterization of unsaturated soils. This relationship is

strongly dependent on the initial dry density and stress paths (Romero and Vaunat 2000). The retention curve of this clay is determined for two different soil states:

- For a slurry clay and then dried denoted by ‘SD’;
- For compacted clay at Optimum Standard Proctor denoted by ‘C’.
- For slurry clay along a desiccation path, the retention curve was determined for an initial void ratio $e_0 = 1.74$ to a final one $e_f = 0.59$. For the compacted clay ‘C’ the initial and final void ratios along the same path corresponded to $e_0 = 0.80$ and $e_f = 0.71$.

Test results show an important dependency of the water retention curve and on void ratio. The van Genuchten parameters are determined through laboratory testing and then used in simulation. Figure 1 shows the water retention curves along desiccation paths.

Table 1. Physical properties of Beja clay.

Soil properties	Value
Solid density (Mg/m^3)	2.70
Liquid limit	62%
Plastic limit	30%
Shrinkage limit	15%
Plasticity index	32%
Fraction of fines (< 75 µm)$^{(1)}$	90%
Clay-size fraction (< 2µm)	33%
Water content under hygroscopic conditions (relative humidity: 50%)	4.3%
Clay minerals (qualitative XRD)	Illite, smectite
Specific surface (mercury intrusion porosimetry)	24 m^2/g

(1)Soil Classification USCS ASTM D-2488.

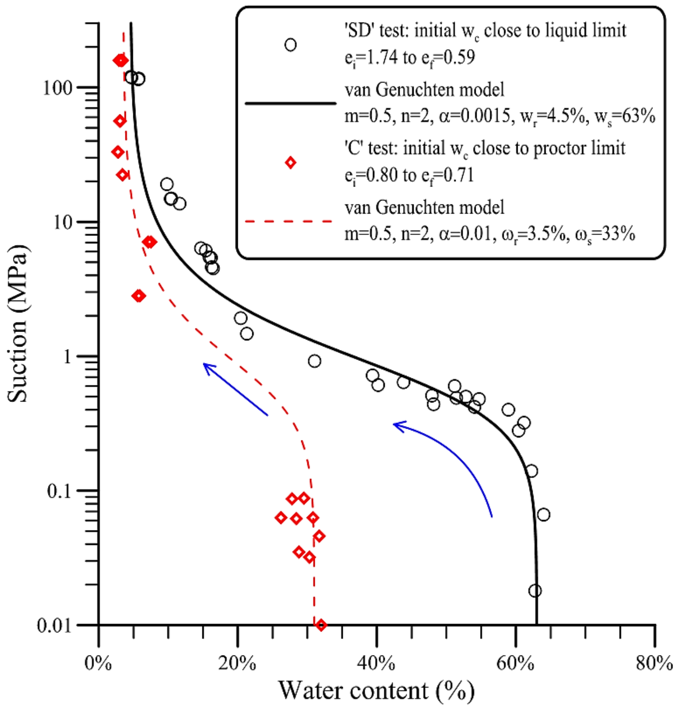

Figure 1. Water retention curves in terms of gravimetric water content starting from Slurry conditions (‘SD’ paths) and Compacted ‘C’ states. van Genuchten model for different states.

Microstructural features have gained increasing importance to improve understanding of phenomenological behavioural features of fine grained soils, as well as in setting out hypotheses for building up constitutive models. Mercury intrusion porosimetry MIP tests on freeze-dried samples have been performed to study the pore size distribution of different samples prepared at given states (‘C’ and ‘SD’). In this regard and if one considers the cracking and tensile strength to be associated with the capability of the porous media to sustain a given suction without appreciable desaturation, this strength is also related, besides water content and porosity, to soil microstructure (pore size distribution).

MIP tests on samples have been performed at two water contents. For the first MIP the on ‘SD’, the pore size distribution is carried out on dried material (w = 24.0% and e = 0.648) starting from saturated (remoulded) state. A second test ‘C’ is performed on dynamically compacted sample at w = 24.4% and e = 1.08.

Figure 2 presents the pore size density function PSD plots for the two states. It can be observed that the ‘SD’ sample displays a mono-modal PSD curve. On the contrary, the compacted sample ‘C’ shows at least two dominant pore modes at sizes (40µm for the macro-pores, and 0.1µm for the micro-pores), in which the presence of large inter-aggregate pores indicates the open structure created during dry-side compaction at e = 1.08. As it can be intuitively anticipated, the presence of macro-pore in ‘C’ decreases the tensile strength and increases the intensity of cracks. To stabilise this critical issue, Alfa fibre is added to the compacted clay.

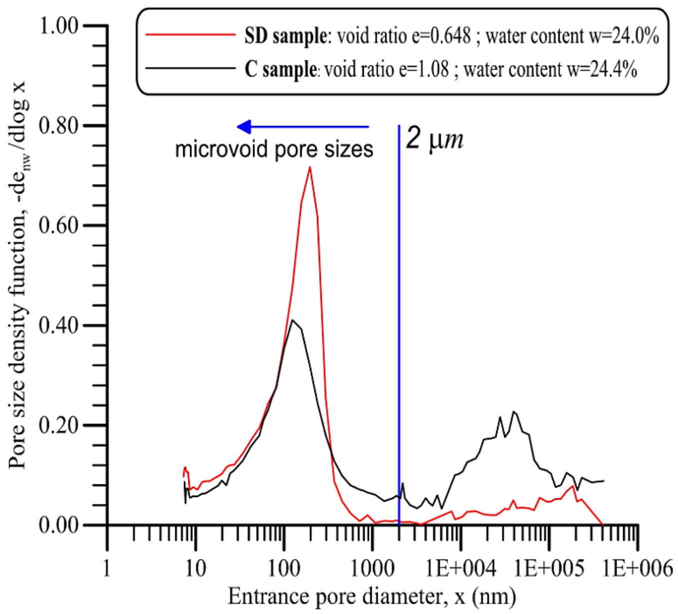

Figure 2. Pore size density functions. Slurry and dried samples ‘SD’ and compacted sample ‘C’.

2.2 *Characteristics of the fibres*

Alfa fibres, which are very abundant in Tunisia, were used in this investigation. They were extracted in the laboratory by the soda process which is a hydrolysis in a Sodium Hydroxide solution (Figure 3). The physical and mechanical properties of these fibres are given in Table 2.

Figure 3. Short Alfa fibres (30 mm in length).

Table2 Physical and mechanical properties of Alfa fibres (Bessadok et al., 2009).

Tensile properties of Alfa fibres	
Young's modulus (GPa)	13
Tensile strength (MPa)	565
Strain at failure (%)	5.8
Fibre density (Mg/m^3)	0.89
Average diameter (mm)	0.3

2.3 *Preparation of the fibre/soil mixtures*

Unreinforced (with a percentage of fibre η_f=0% by dry mass) and reinforced specimens with Alfa fibres (η_f=0.3%) with 30 mm length were prepared. The short length fibres were considered to stop the micro cracks. The soil was initially dried at 60°C, broken into pieces, and then passed through a 2-mm-sieve. Fibres were mixed manually with the soil while adding water in small increments. The specimens (100x100x20 mm) were compacted at maximum dry density (1.5 Mg/m^3) and optimum gravimetric water content (23%).

3 EXPERIMENTAL RESULTS

3.1 *Crack patterns*

A digital camera was installed to record the surface during desiccation at fixed time intervals of 3 hours. The surface was uniformly illuminated with oblique incident light from some lamps. The two experiments were carried out in succession using the same experimental setup and the same conditions for desiccation in terms of temperature and relative humidity. The crack patterns obtained during desiccation are shown in Figure 4.

Figure 4 shows typical appearance and evolution of cracks in unreinforced and fibre-reinforced specimens at three different desiccation elapsed times of 0h, 12h and 24h. The unreinforced soil specimen forms a characteristic hierarchical cracking pattern, primarily governed by subdivision. The primary cracks propagate faster through the entire depth. They are longer, wider, and divide the clay mass into large cells. However, for the Alfa fibre reinforced specimen, the cracks are shorter. It can be deduced from the results that the inclusion of 0.3% of Alfa fibres leads to a significantly decrease of cracking extent and propagation.

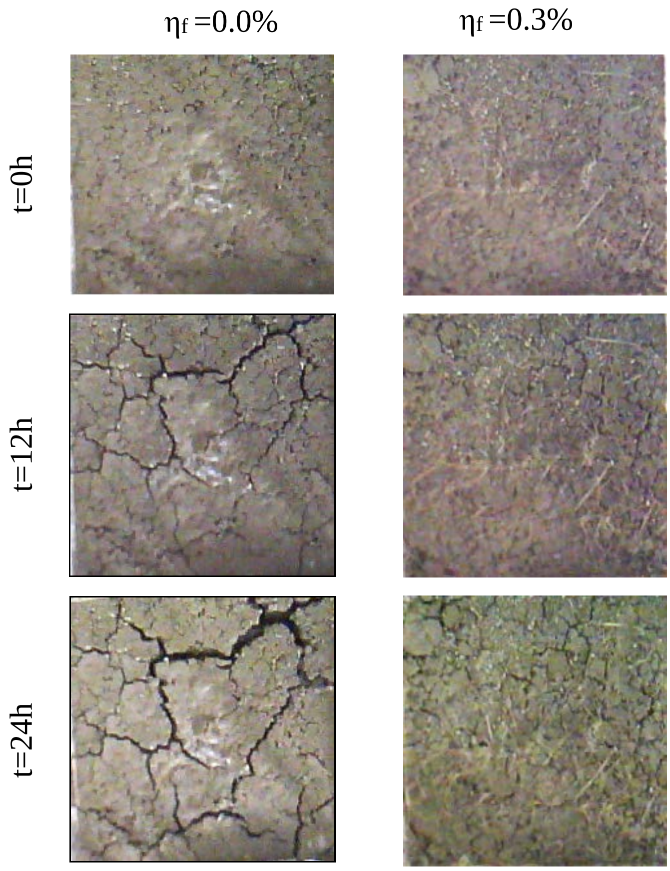

Figure 4. Crack pattern evolution during desiccation, a comparison between unreinforced and reinforced compacted clay with Alfa fibres (a square soil sample of 100x100x20 mm).

3.2 *Evaporation and crack effects*

The interaction between the atmosphere of the climatic chamber and the soil is the most important factor that can induce desiccation (drying of soil by evaporation of water at surface with contact of air). The temperature of the tests carried out in the climatic chamber was fixed at 30±2°C. Figure 5 presents the variation of both relative humidity and water content for unreinforced and reinforced specimens.

We propose a new analytical model presented in equation (1) to predict the water content variation during time. The parameters of water content model that uses a complementary error function are presented in Table 3.

$$w(t) = (w_0 - w_r).erfc(t / T_0) + w_r \qquad (1)$$

where w_0 is the initial water content, w_r is the residual water content, and T_0 is the time corresponding to residual water content (Hours).

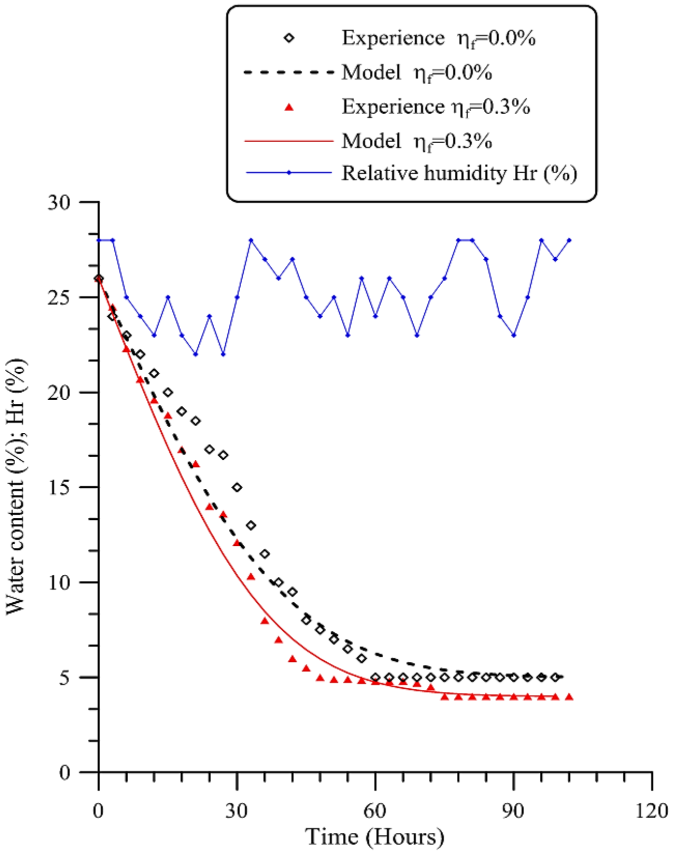

Figure 5. Comparison of measured water content and analytical model for unreinforced and reinforced compacted clay.

Table 3. Parameters of water content equation (1) for the two specimens.

η_f (%)	w_0 (%)	w_r (%)	T_0 (Hours)
0.0	26	5	45
0.3	26	4	40

Three observations can be found:

i. For the reinforced soil, the variation of water content with time is found to be more linear than for the unreinforced one. The propagation of cracks in unreinforced soil has led to an increase of porosity and then of the surface of contact with air. The rate of evaporation is faster than the one observed for the reinforced soil. The reinforced clay is stabilised with Alfa fibres and the crack surface is reduced. This has induced a more regular linearity for the water content variation.

ii. The residual water content is a little bit lower for reinforced clay and this could be since the bulk density of fibres is lower than the bulk density of clay.

iii. It can be also observed that analytical results to predict the water content variation during time are in good agreement with the experimental ones.

4 NUMERICAL RESULTS

4.1 *Updated model*

In the following, the numerical treatment of the desiccation and cracking problem is briefly presented. The discretization of the equations with respect to space and time followed by the linearization of the coupled system of equations is not presented in this short study. Furthermore, the algorithmic procedure is discussed in Trabelsi et al. (2010) and Trabelsi (2014).

In this study, the model proposed by Trabelsi et al (2012) is updated to consider fibre effects. Only the equation of tensile strength is modified, and the geometry is updated. The same parameters are used in this work since the same soil is used. It was found that, cohesion was influenced not only by suction, but also by fibre content, as indicated by the proposed equation:

$$C_s(s) = A_f \times s + B_f \qquad (2)$$

where A_f and B_f are material parameters introducing the effect of fibre reinforcement on cohesion. B_f is the cohesion of the saturated soil and A_f is the slope of the variation of cohesion with suction. In addition to suction, cohesion of unreinforced and reinforced soil is related also to porosity. A relationship between cohesion and porosity can be deduced using a function that relates tensile strength with porosity. When the composite tends to shrink, the propagation of crack is interrupted by fibre bridging effect. Consequently, the macro porosity evolution is delayed resulting in the increase of ductility. The following function expressing dependence on porosity and on fibres content is proposed:

$$C_\phi(\phi) = (1 - \eta f)\left(\max\left(\left(1 - \left(\frac{\phi}{\phi_0}\right)^{n_0}\right); 0\right)\right) + \eta f\left(\max\left(\left(1 - \left(\frac{\phi}{\phi_1}\right)^{n1}\right); 0\right)\right) \qquad (3)$$

where ϕ is the porosity of the composite, ϕ_0 and ϕ_1 are the average porosity of unreinforced soil and the composite respectively for which tensile stress is minimum or nil; n_0 and n_1 are material parameters characterizing the plasticity / ductility of the clay matrix and the fibre elongation, respectively. Parameter n_0 may be related to the plasticity index; it increases with the plasticity index. While parameter n_1 can be related to the plastic deformation of fibres and its increase leads to more ductility of the composite. η_f is fibre content and must be < 1%. For η_f =0%, C_ϕ (ϕ) decreases suddenly and the clay matrix loses all its cohesion. The value of porosity corresponding to the total loss of soil matrix cohesion is estimated to be 0.6 for the clay of Thibar. This was proposed by Trabelsi et al. (2012) after conducting a series of tensile tests on specimens dried at various dry densities (different porosities). By examining Figure 6, it can be observed that an increase in η_f leads to some increase in cohesion when porosity increases over 0.6. Accordingly, this function makes the model able to reproduce the effect of fibres on ductility.

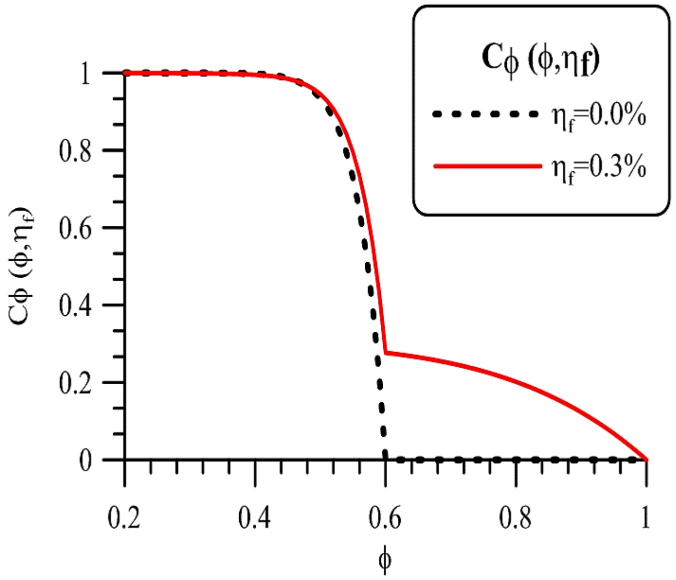

Figure 6. Cϕ versus porosity.

By combining the new functions between cohesion depending on suction (eq 2) and decrease function C_ϕ (eq 3) depending on porosity and fibre reinforcement, the proposed model can therefore be written as:

$$C = C_\phi(\phi, \eta_f) C_s(s) \quad (4)$$

4.2 *Numerical results.*

To validate the proposed numerical model and to show its consistency with the reality, a comparison with experimental results was made. The same conditions were reproduced in the different simulations. Firstly, the same geometry of the experimental mould was chosen for the simulated sample (a square soil sample of 100x100x20 mm). Secondly, a field of randomly distributed porosity has been given as initial condition, with a given average initial porosity and a standard deviation equal to 1% of the given average value. This heterogeneity is intended to facilitate the initiation and propagation of cracks in a more realistic way.

The saturation profile was imposed at the beginning of the tests. An intermediate and final saturation, suction and water content profile was assigned, based on laboratory measurements made during some days of desiccation. The simulations were made with a first mesh of 3618 tetrahedral elements. The thickness (distance in the vertical direction) is divided into five elements.

The concentration of vapour in the air within the sample is almost constant, of the order of 0.0356 kg/kg. The concentration of vapour in the air in contact with the top surface is imposed to a 0.011 kg/kg value (correspond to relative humidity H_r=30%). This boundary condition is going to generate a hydric transfer with the environment through the top surface. This hydric flow increases the suction and causes a reduction of volume (shrinkage).

The crack pattern evolutions for η_f=0.0% and η_f=0.3% respectively are presented in Figure 7. During the simulations, the vertical deformation was limited to almost zero by imposing a smaller shrinkage coefficient α_v. We observed that in the element where the tensile strength is exceeded, the crack initiates and begins to propagate from this point. Crack pattern initiation and propagation depend on fibre content value (η_f).

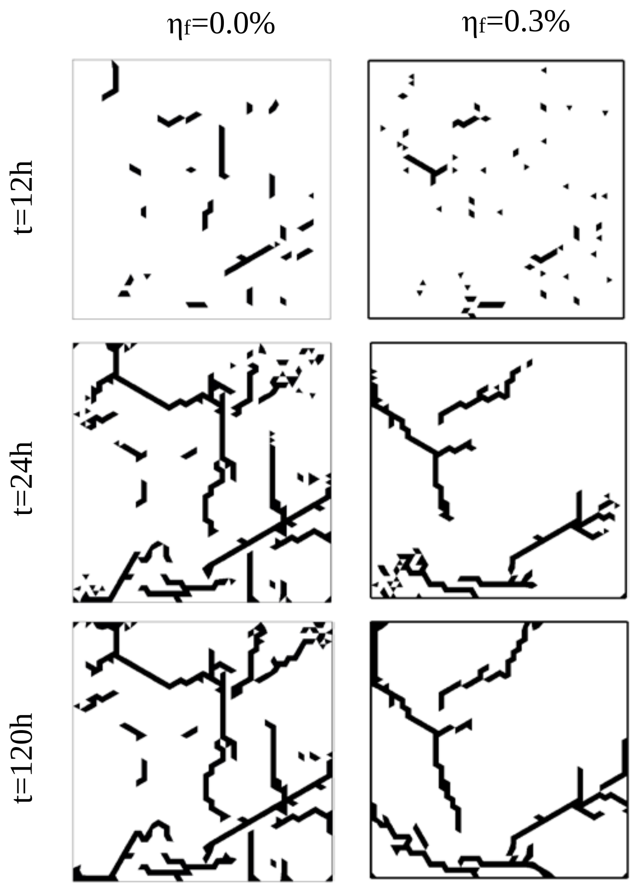

Figure 7. Crack pattern evolutions at the surface.

Figure 8 shows the final crack patterns presented in three dimensions 3D for unreinforced and reinforced compacted clay. For the compacted clay, cracks start at surface and propagate to the bottom. Figure 8a presents a dense crack network for unreinforced compacted clay. It can be easily observed that crack distribution is significantly reduced by inclusion of Alfa fibres (Figure 8b).

Figure 9 shows the variation of the Crack Intensity Factor CIF for both experimental and numerical tests. The recorded CIF was 11% and 5% respectively for unreinforced and reinforced specimens. The same values were found by both numerical and experimental results suggesting that the model is quite able to predict the crack propagation induced by desiccation phenomena.

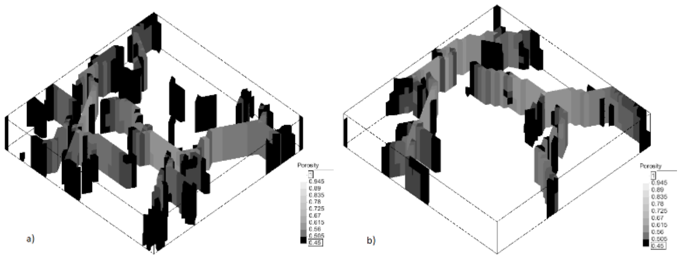

Figure 8. 3D crack pattern at time t=120h, a) unreinforced b) reinforced.

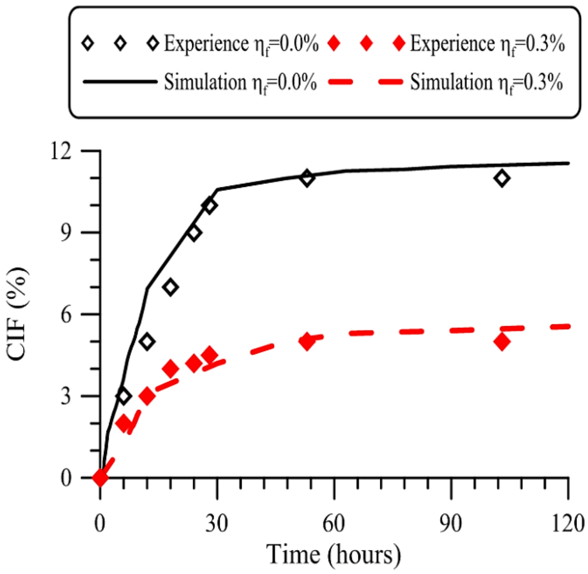

Figure 9. Crack Intensity factor (CIF) evolution during desiccation, a comparison between experimental and numerical simulation for unreinforced and reinforced compacted clay with Alfa fibre.

4.3 *Numerical and analytical comparison*

The analytical model proposed in equation 1, describing the variation of water content during the time for homogenous porous media, is in good agreement with the numerical results of the simulated tests (Figure 10). The numerical model based on experimental constrained desiccation tests allowed exploring the influence of the cracks.

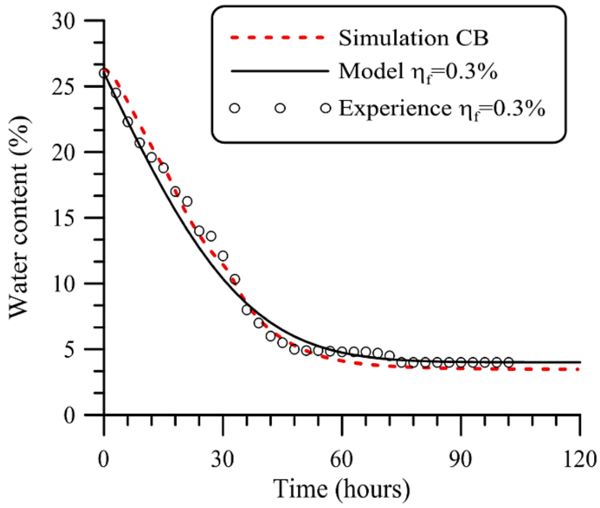

Figure 10. Comparison of measured water content, analytical model and simulation for reinforced compacted clay.

5 CONCLUSION

In this work, the effect of Alfa fibre reinforcement on crack propagation induced by soil desiccation was investigated. The results showed that the soil desiccation cracking behaviour was significantly influenced by fibre inclusion, which was demonstrated by the evolution of the crack intensity factor along the desiccation process. Moreover, the newly developed numerical model was found quite able to reproduce experimental results, particularly the evolution of the crack intensity factor.

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