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The permeability of natural fibre drains, capturing their micro-features

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Abstract

Natural fibres such as jute and coir are emerging as distinct alternatives to synthetic geomaterials, and in recent years they have been used increasingly for drainage and filtration in field applications. However, these naturally occurring materials are extremely variable in micro-characteristics such as the size, uniformity and shape of their fibres, while there is a lack of studies addressing how these differences can affect the hydraulic behaviour of fibrous media. This paper offers a laboratory study of the influence of micro-features on the hydraulic conductivity of fibre drain. Non-twisted and twisted fibre drains made from jute and coir were subjected to hydraulic conductivity testing and micro-analyses. Experimental results show a considerable contribution of the size characteristics of fibre to the hydraulic behaviour of the drain. A less-rounded shape of fibre and a larger twisting angle of the drain can increase the fluid-fibre contact area and the corresponding tortuosity of flow, which significantly reduces the drain permeability. The way in which the Kozeny-Carmen analytical approach can be adopted to predict the permeability of a fibre drain is discussed based on the experimental results, considering various micro-factors including the size of fibre, uniformity and the associated porosity.

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The permeability of natural fibre drains, capturing their micro-features

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Natural fibres such as jute and coir are emerging as distinct alternatives to synthetic geomaterials, and in recent years they have been used increasingly for drainage and filtration in field applications. However, these naturally occurring materials are extremely variable in micro-characteristics such as the size, uniformity and shape of their fibres, while there is a lack of studies addressing how these differences can affect the hydraulic behaviour of fibrous media. This paper offers a laboratory study of the influence of micro-features on the hydraulic conductivity of fibre drain. Non-twisted and twisted fibre drains made from jute and coir were subjected to hydraulic conductivity testing and micro-analyses. Experimental results show a considerable contribution of the size characteristics of fibre to the hydraulic behaviour of the drain. A less-rounded shape of fibre and a larger twisting angle of the drain can increase the fluid–fibre contact area and the corresponding tortuosity of flow, which significantly reduces the drain permeability. The way in which the Kozeny–Carmen analytical approach can be adopted to predict the permeability of a fibre drain is discussed based on the experimental results, considering various micro-factors including the size of fibre, uniformity and the associated porosity.

Notation

A_o	specific surface
A_t	interior cross-sectional area of the tube
c	shape factor
D_f	diameter of fibre
i	hydraulic gradient
K	permeability
k	hydraulic conductivity
k_k	Kozeny constant
L	characteristic length
n	porosity
Re	Reynolds number
R_t	correction factor for the viscosity of water
t	tortuosity of flow
U_f	flow velocity
U_s	discharge (superficial) velocity
V_w	water volume collected at the outlet
θ	twisting angle of fibre drain
ν	kinetic viscosity
σ_v	coefficient of variation

1. Introduction

Synthetic materials have been used extensively in many geo-engineering applications such as reinforcement (Yin, 1997; Zhan and Yin, 2001), separation (Arulrajah *et al.*, 2009) and

drainage (Chu *et al.*, 2009; Indraratna *et al.*, 2012; Kelly, 2014), but these polymer-based solutions have raised concerns from ecological and biological perspectives because polymeric materials are resistant to biodegradation (Nicholson, 2006) and are thus harmful to the natural environment (Gregory and Andrady, 2003). This is why geomaterials made from natural fibres such as jute and coir have received favourable attention in recent times for applications such as erosion control (Midha *et al.*, 2014; Vinod and Minu, 2010), reinforcement (Babu and Vasudevan, 2007; Subaida *et al.*, 2009; Vinod and Bhaskar, 2012) and soft soil improvement (Asha and Mandal, 2015; Beena and Babu, 2008; Indraratna *et al.*, 2016; Kim *et al.*, 2001). These naturally occurring materials not only have beneficial engineering characteristics, but also are biodegradable over time. More importantly, natural fibres are abundant in many developing regions, particularly in south and southeast Asian countries, so a wider application of these materials can certainly bring considerable social and economic benefits to local populations.

The most commonly used natural fibres in geoenvironmental engineering are jute and coir, with India and Sri Lanka being the major producers of coir fibre, followed by Thailand, Vietnam, the Philippines and Indonesia (Ali, 2010), while more than 90% of the world's jute is manufactured in Bangladesh, China, India

and Thailand (Rahman, 2010). Coir fibre extracted from coconut husks contains more than 40% lignin (Gupta, 2011), making it more robust and durable than other natural fibres such as jute, which contains more than 80% cellulose and only around 12% lignin (Som *et al.*, 2009). Note that more lignin means that the fibre can resist biodegradation better. The durability of natural fibres also depends on environmental conditions such as humidity, temperature, acidity and the biological properties of the soil (Kim and Cho, 2008; Saha *et al.*, 2012). Other natural fibres such as straw, bamboo and hemp are abundant in many agricultural regions such as Vietnam and Thailand.

Most natural fibres are used for filtration and drainage based on their distinct hydraulic conductivity. There are numerous studies (Gebart, 1992; Sullivan, 1942; Xu and Yu, 2008; Yazdchi *et al.*, 2012) addressing the hydraulic behaviour of fibrous media, but most of them only consider idealised arrangements of fibres such as quadratic and hexagonal parallel arrangements (Gebart, 1992; Nakayama *et al.*, 2007; Tamayol and Bahrami, 2009), whereas the natural fibres used in geo-engineering have a more complex porous structure where the fibres are disordered and twisted (Nguyen and Indraratna, 2016a). Furthermore, when investigating the hydraulic behaviour of natural fibre drains, many studies only concentrated on the macro-perspectives such as the discharge capacity of the whole drain (Asha and Mandal, 2012; Venkatappa Rao *et al.*, 2000), while ignoring the micro-aspects such as the shape, size and uniformity of fibres, which can have a significant influence on the permeability of fibrous media (Ozgumus *et al.*, 2014; Williams *et al.*, 1974). It is therefore necessary to study the micro-characteristics of natural fibres arranged in a more practical form and examine how these influence their hydraulic conductivity.

To predict the permeability of a porous medium, the analytical method proposed by Kozeny (1927) and later modified by Carman (1937) (known as the Kozeny–Carmen (KC) method) is preferred in practice due to its computational simplicity. Note that this is a semi-empirical method that requires the Kozeny constant k_k to be determined according to the particular micro-features of the medium. While numerous studies have determined this constant for uniform porous media, not many have used this approach to the natural fibres used in geoengineering where the elemental particles are less homogeneous. As the constant k_k is very sensitive to the micro-characteristics of the medium (Ozgumus *et al.*, 2014; Xu and Yu, 2008), how this coefficient varies over the micro-parameters and its implication for natural fibres such as coir and jute must be investigated.

The aim of this study is therefore to clarify the hydraulic behaviour of the typical natural fibres used in geoengineering, such as jute and coir, by an experimental scheme. Micro-analyses of fibre drains are carried out and the influence of

micro-characteristics on the hydraulic conductivity of the drain is presented. The KC method is applied and validated with experimental results, and a suggestion on how to use this method in practice is made.

2. Analytical method to estimate the permeability of fibre drains

The permeability of a porous medium can be predicted by the KC approach as follows

$$1. \quad K = \frac{1}{k_k A_o^2} \frac{n^3}{(1-n)^2}$$

where K is the permeability, n is the porosity, k_k is the so-called Kozeny constant determined empirically, and A_o is the specific surface of the media defined as the ratio of the fluid–solid interfacial surface to the solid volume in a given fluid–solid system. If a medium consists of individual fibres in a certain arrangement, A_o actually becomes the ratio of the perimeter to the cross-sectional area of the fibres, so it actually varies with the shape of the fibre particles; for example, with cylindrical fibres Equation 1 can be re-written as

$$2. \quad K = \frac{1}{16k_k} \left(\frac{\sum_{i=1}^{n_f} D_{f,i}^2}{\sum_{i=1}^{n_f} D_{f,i}} \right)^2 \frac{n^3}{(1-n)^2}$$

where $D_{f,i}$ is the diameter of the fibre i , and n_f is the number of fibre particles in the medium. If all the fibres have a uniform diameter (e.g. D_f), then Equation 2 can be simplified as

$$3. \quad K = \frac{D_f^2}{16k_k} \frac{n^3}{(1-n)^2}$$

Although most studies agree that K is proportional to $n^3/(1-n)^2$, there is a certain variation when considering other parameters in the KC method. The most common preferences (Choi *et al.*, 1998; Gutowski *et al.*, 1987; Sullivan, 1942) are using the Kozeny constant k_k independently with the diameter D_f , so that k_k varies with other micro-characteristics of the medium such as the porosity and fibre arrangement. Others such as Rodriguez *et al.* (2004) and Yazdchi *et al.* (2012) simplified the method further by combining D_f and k_k into one parameter that is also determined empirically.

Obviously Equation 3 is applicable for idealised conditions where fibres are uniform, whereas Equations 1 and 2 are much more complicated in determining A_o and the diameters of individual fibres $D_{f,i}$ in the medium, so it is better to use an average diameter $D_{f,a}$ to represent all of the single fibres. $D_{f,a}$ can vary widely with fibres such as jute and coir, and with different manufacturing techniques, so a prior investigation is

needed to obtain this representative parameter accurately before applying the KC equation. It is also important to note that the average diameter approach can lead to a certain inaccuracy in the predicted permeability because natural fibres such as jute and coir are clearly non-uniform, and therefore this can potentially result in a different behaviour of k_k compared with a conventional application of the KC method in homogeneous particulate media.

Over the years enormous effort has been made to determine k_k for fibrous media. Studies such as those by Gebart (1992), Gutowski *et al.* (1987) and Li and Gu (2005) adopted a constant k_k unchanged over varying porosity, whereas others (Choi *et al.*, 1998; Rahli *et al.*, 1997; Xu and Yu, 2008) suggested a porosity-dependent k_k . Kyan *et al.* (1970) proposed an analytical solution incorporating micro-porous parameters into the calculation of k_k such as the porosity, diameter and the tortuosity of fibre media. Numerous studies (Choi *et al.*, 1998; Gutowski *et al.*, 1987; Li and Gu, 2005; Yazdchi *et al.*, 2012) also attempted to link k_k to the tortuosity t , which is defined as the ratio of the actual flow path to the straight length of a fibre drain, as given by

$$4. \quad k_k = ct^2$$

where c is the shape factor representing the influence of the cross-sectional shape of fibres, and c is defined as the ratio between the surface area of the fibre and the surface area of a sphere with the same volume (Li and Gu, 2005). With cylindrical fibre, the shape factor reaches its minimum value ($c=1$) where the tortuosity t depends on how the fibres are arranged in the bundle. A perfectly parallel arrangement of fibres has the shortest fluid path, resulting in a unity of t . According to this approach, cylindrical fibres arranged in parallel have the smallest k_k and the highest permeability.

3. Experimental investigation into the permeability of fibre drains

3.1 Fibre drain

A natural fibre drain that is actually a combination of individual fibres in a certain arrangement is usually employed for drainage where the fluid flows in the void between those fibres (Kim and Cho, 2009; Lee *et al.*, 1994; Venkatappa Rao *et al.*, 2000). At present there are a variety of fibre drains made from different natural fibres such as jute, coir and straw, with either a circular or band-shaped cross-section (Beena and Babu, 2008; Kim *et al.*, 2001). Of the existing naturally occurring materials, coir and jute are the most preferable due to their favourable engineering characteristics and abundance in developing regions. Despite such a variety of structures and materials, the discharge capacity of the whole drain relies on the hydraulic properties of its elemental fibre bundles. In this study, brown coir and jute fibres were used to generate

elemental fibre drains, which were then subjected to an experimental investigation into the hydraulic conductivity of the fibres.

In this study, there were two basic fibre arrangements, non-twisted and twisted bundles (Figure 1). The non-twisted bundles meant individual fibres were placed in almost parallel arrays without twisting, whereas fibres in the twisted structure were packed and twisted together around the longitudinal axis of the bundle, such that the larger the twisting angle, the more the fibres were tightened and pressed together. The fraction of fibres in a drain was approximately manipulated by the quantity of single fibres packed into the drain; the more the fibres packed, the denser the bundle. In this current approach, the fibres were placed randomly into a bundle while previous studies (Gebart, 1992; Nakayama *et al.*, 2007) investigated fibres arranged in particular forms such as square and hexagonal arrays because in geoenvironmental applications the disordered arrangement of fibres is overwhelming.

To create a fibre drain for testing in a consistent manner to ensure reproducibility of results, individual fresh fibres (almost straight and longer than 150 mm) were selected and arranged in parallel. The two ends of the bundle were confined by a thin ring. The bundle was then placed in a long tube (4 mm inner diameter and 100 mm long) by pulling its ends. While one end of the bundle was fixed, the other end was rotated gradually, making the whole bundle twisted to the desired twisting angle. The two ends of the bundle were then trimmed to ensure that all fibres would have the same length (i.e. 100 mm). For non-twisted bundles, the twisting step was skipped. By this process, fibre drains having different twisting angles were generated. In this study, there were 44 coir and 19 jute bundles generated for different objectives of the investigation.

The physical properties of jute and coir such as density and average diameter were determined in the laboratory using an optical microscope. Figure 2 shows the size distribution of the jute and coir fibres used in this study. The equivalent diameter of jute varied from 10 to 85 μm , but more than 75% of the fibres were between 25 and 55 μm in diameter. The mean diameter of jute was 41.8 μm , which was within the common ranges reported by previous studies, such as 54 μm by Defoirdt *et al.* (2010). Unlike jute, the dimensions of coir were much larger; its diameter ranged from 90 to 502 μm , with a mean value of 235 μm . The most common diameters of coir fibre were from 150 to 300 μm , and this accounted for more than 70% of total fibres. The densities of jute and coir were 1415 and 1105 kg/m^3 , respectively. These parameters were corroborated with those reported in previous studies (Defoirdt *et al.*, 2010; Gupta, 2011).

Figure 3 shows how the cross-sectional shapes of coir differed from those of jute. Coir had almost round cross-sections, whereas jute had very complex polygonal shapes that varied

Figure 1. Fundamental bundles of jute and coir drains: (a) non-twisted fibres and (b) twisted fibres

Figure 2. Distribution of the average diameter of jute and coir: (a) size distribution of coir fibre and (b) size distribution of jute fibre

from square and rectangular to irregular ones. These differences in the geometric features of jute and coir fibres resulted in drains with different porous characteristics.

3.2 Hydraulic conductivity test on fibre drains

Two approaches are generally used to determine the hydraulic conductivity of fibrous materials, either a unidirectional or a radial flow (Sharma and Siginer, 2010). A fluid flow with a low injection pressure is used to ensure that the fibres remain in a static condition by controlling either the velocity or the pressure of the inlet fluid while the fluid is flowing. In this study, the pressure controlled model that has been used commonly in previous studies (Rahli *et al.*, 1997; Sullivan, 1942; Williams *et al.*, 1974) due to its simplicity was adopted (Figure 4).

A key objective of this study is to investigate the influence of micro-characteristics on the hydraulic behaviour of natural fibre drains. In this regard, for the purpose of simplicity, the actual role of the interaction between the soil and drain fibres (i.e. soil–drain interface effects) has not been quantified within the scope of this paper. However, it is noteworthy that for many in situ applications, the influence of the soil–fibre drain interaction on the hydraulic behaviour of the drain can be a significant factor, and this will be evaluated in a future study.

The tube holding the fibre drain used for the hydraulic test had a smooth internal surface to minimise the friction that could affect fluid flow, and the inlet was connected to a constant head water tank. Moreover, manometers were used to

Figure 3. Cross-section of fibres in the 4 mm dia. tube: (a) cross-section of jute fibres and (b) cross-section of coir fibres

measure the water heads at the inlet and outlet of the tube to an accuracy of 1 mm. The difference in pressure between the inlet and outlet of the tube was adjusted by changing the relative height between the tube and the water tank. Water was flowed from the inlet through the fibre drain and was measured at the outlet of the tube under different heads of water. Based on the volume of water discharged at the outlet over time, the hydraulic conductivity of the fibre bundle was obtained. Note that the hydraulic gradient was determined with respect to the length of the fibre drain and the difference in the water heads at the two ends of the tube.

The effect of friction between the walls of the tube and the fluid on the discharge velocity of flow was evaluated by measuring the loss of water heads between the inlet and outlet over varying discharge velocities when water was flowing through the vacant tube. The result showed an insignificant loss in the water head for medium and dense fibres, where the flow velocity was small and where the internal surface area

of the tube was relatively insignificant compared with the total surface area of the fibres. However, for loose media (e.g. $n > 0.85$), friction at the fluid wall could account for ~12 and 31% of the total water heads for jute and coir drains, respectively. Previous studies by Sullivan (1942) using a 8.31 mm dia. and 50.5 mm long copper tube, and by Williams *et al.* (1974) employing a 5 mm dia. and 150 mm long glass tube also considered the effect of the boundary, and pointed out that this disturbance could be omitted for fine fibres but must be considerable for coarse fibres (i.e. $D_f > 50 \mu\text{m}$).

After the hydraulic test, the fibres were subjected to a post-processing, which enabled their micro-characteristics to be captured. The tube containing fibres was dried by gently blowing warm dry air through the tube. To maintain the original structure of the fibrous system after the hydraulic test, the fibre tube was then immersed into resin mixed with a hardener to cast samples. These samples holding micro-porous information of the fibre bundles were then subjected to micro-analyses.

Figure 4. Schematic diagram of experimental model to determine hydraulic conductivity of fibrous drain

Photos of the cross-section of the hardened fibre tubes were taken with an optical microscope. The image analysis techniques available in the ImageJ software (Rasband, 2014) were implemented on these photos to obtain micro-porous properties of the drains such as the cross-sectional area of resin (void) and solid fibres; these parameters also enabled the porosity of the drain to be estimated. Note that the colour of resin representing the drain voids (Figure 3) was very different to that of the solid fibres, enabling easier determination of porosity by using area measurement techniques on ImageJ. The porosity of a bundle was measured at different positions – that is, two ends and one at the middle of the bundle, and then an average value was used.

With respect to the water volume V_w obtained at the outlet of the fibre tube over time t , the hydraulic conductivity k was determined by

$$5. \quad k = \frac{V_w R_t}{i A_t t}$$

where R_t is the correction factor for the viscosity of water, depending on the water temperature (ASTM, 2008); A_t is the interior cross-sectional area of the tube and i is the hydraulic gradient. Note that, in this experiment, fluid flow was investigated under a small difference in water heads to ensure laminar flow, while the discharge volume was measured at a steady state of flow. The water used in the experiment was $\sim 19^\circ\text{C}$, and under these conditions the kinetic viscosity of water was $1.002 \times 10^{-6} \text{ m}^2/\text{s}$ (Massey and Ward-Smith, 2006).

4. Results and discussion

4.1 Discharge velocity over a hydraulic gradient

The discharge capacity of a drain must be considered with respect to the hydraulic gradient at which it is measured (Chu *et al.*, 2004). The variation of the discharge velocity (superficial velocity U_s) over the hydraulic gradient (i) of the fluid flow recorded in the experiment for typical coir and jute

Figure 5. Variation of discharge velocity U_s over hydraulic gradient

fibre drains, including loose ($n > 0.8$) to dense ($n < 0.5$) media, is shown in Figure 5. Here the larger the hydraulic gradient, the higher the discharge velocity. The relationship between U_s and i is almost linear when i is small enough to maintain laminar flow where $U_s = k \times i$ (Darcy law). However, this relationship becomes non-linear when i increases, which indicates that the flow would turn into a turbulent transition zone where the inertial part of the flow is larger. The turning point between the laminar and turbulent transition zones occurs earlier when the fibres are looser; for example, loose fibre drains have a turning point at $i = 0.3$ and $i = 0.5$ for coir and jute fibres, respectively, but this gradually increases as the porosity of the fibre drains decreases. This occurred because the looser fibres had a higher flow velocity, leading to a larger contribution of inertial flow. Note that the well-known Reynolds number ($Re = U_f L / \nu$, where U_f is the flow velocity, L is the characteristic length and ν is the kinetic viscosity), which is commonly used to evaluate the flow state, is proportional to the fluid velocity (Massey and Ward-Smith, 2006).

Previous studies (Akagi, 1994; Rawes, 1997) have suggested that the largest hydraulic gradient needed to maintain laminar flow in discharge capacity tests of conventional drains should be from 0.1 to 1, depending on the features of the testing models such as scale, confining pressure and drain characteristics. In this study, the hydraulic conductivity of fibre drains was considered in conjunction with laminar flow, so that the discharge velocity was only adopted at small values of i (i.e. $i < 0.3$ for loose fibres and $i < 1$ for medium and dense fibres).

4.2 Influence of the size of fibres in drains

The average diameter of natural fibres varies widely from several micrometres (e.g. silk) to hundreds of micrometres (e.g. coconut coir), and that can cause a difference in their hydraulic behaviour. To clarify how differences in the size of fibres could affect the hydraulic behaviour of drains, only coir fibre, which had been shown to be more homogeneous and larger in size than jute, was used for this investigation. Also, only coir fibres were used to remove any influence that the difference in the shape and surface of fibre between jute and coir might have on the experimental result. Since the diameter of individual fibres in a bundle can vary widely (Figure 2), the

dispersion in the diameter of a fibre medium also needs evaluation through the coefficient of variation σ_v , which is defined as the ratio of the standard variation to the mean fibre diameter, such that a smaller σ_v indicates more uniform fibres in the drain.

4.2.1 The mean diameter of fibres in a bundle

For this aspect of the investigation, hydraulic tests were carried out on coir bundles having different mean (average) diameters. Three sets of fibres with mean diameters of $D_{f,a} = 155$, 239 and 376 μm were generated (Figure 6), and a non-twisted type of drain was used. Note that for each level of mean diameter, the hydraulic test was conducted over varying porosity (different bundles). Fibres in a bundle in this investigation were highly uniform in diameter; in particular, the coefficient of variation varied in a small range from 8.7 to 11.2% for all bundles.

The influence that the mean diameter of fibres in a drain has on its hydraulic conductivity is shown in Figure 7. It is interesting that the drain formed by the larger diameter fibres results in a higher permeability for the same porosity. For example, with $n = 0.6$, the hydraulic conductivity of the drain

Figure 6. Coir drains with different fibre diameters: (a) big size $D_{f,a} = 376 \mu\text{m}$; $n = 0.59$; (b) medium size $D_{f,a} = 239 \mu\text{m}$; $n = 0.55$; (c) small size $D_{f,a} = 155 \mu\text{m}$; $n = 0.62$

Figure 7. Influence of fibre size on the hydraulic conductivity of coir fibres

is 3.1×10^{-3} m/s for the smallest fibres, and this increases to 9.0×10^{-3} and 21×10^{-3} m/s when $D_{f,a}$ increases to 239 and 376 μm , respectively. The gaps between the three curves are larger when the fibre drain is denser. Particularly when the fibre drain is loose ($n=0.85$) and $D_{f,a}$ increases from 155 μm to 239 and 376 μm , the hydraulic conductivity is 1.74 and 2.39 times higher, respectively. However, this increase in permeability is larger at $n=0.55$ where k increases by a factor of 2.89 and 7.78, respectively, for the same increments in fibre size. This dependence of hydraulic conductivity on the size of the fibre was understandable because the drain with a larger mean diameter had a smaller contact area between the fibres and fluid despite the constant fibre fraction over different sets of fibre drain, leading to the drain having a higher permeability.

4.2.2 The uniformity of fibre diameter

In this investigation, fibre drains were made from coir with different ranges of uniformity (σ_v), but the same mean diameter and porosity were generated without twisting. Figure 8 shows how the diameter uniformity of fibres in a drain can affect its hydraulic conductivity, and although fibre drains have almost the same porosity and mean diameter varying in a small range from 227 to 254 μm , the greater their uniformity (lower σ_v) the higher the permeability of the drain. For example, when $n=0.65$, k decreases from 2.0×10^{-2} m/s at $\sigma_v=10\%$ to 1.4×10^{-2} and 0.71×10^{-2} m/s at $\sigma_v=20$ and 30% , respectively. This decrease in k is sharper when the range of fibre size in the drain is wider, particularly in a denser fibre drain. When $n=0.45$, k decreases by a factor of 1.7, from 2.1×10^{-3} to 1.2×10^{-3} m/s when σ_v increases from 10 to 20% , but there is a more severe reduction by a factor of 5.37 as σ_v reaches 30% . It is also interesting that the influence of fibre uniformity on the permeability of the drain is less as the drain becomes looser. When $n=0.85$, k decreases slightly from

Figure 8. Influence of the uniformity on the hydraulic conductivity of fibres

1.8×10^{-1} m/s at $\sigma_v=10\%$ to 1.5×10^{-1} and 1.03×10^{-1} m/s at $\sigma_v=20$ and 30% , respectively.

The dispersion in the size of fibres affected the permeability of the drain because when the size of fibres was distributed over a wider range, more fibres with a smaller diameter, which had been shown to reduce the permeability of fibre media, were created. As a result, the less-uniform fibres had the greater frictional contact area between fibres and fluid, leading to a lower hydraulic conductivity in the drain.

4.3 Hydraulic conductivity of jute and coir drains

4.3.1 Comparison of hydraulic behaviour of jute and coir fibres

Figure 9 shows how the hydraulic conductivity of jute and coir fibres is related to the porosity of a drain. In this series of hydraulic tests, the mean diameters of fibres in different drains were noted to ensure that their deviations were $<5\%$ for coir and 10% for jute to minimise the influence of fibre size, as discussed in previous sections of this paper. The coefficient of variation σ_v in the diameter of fibres in a drain varied from 25.6 to 31.3% and 36.2 to 44.8% for coir and jute, respectively. The figures show that, as porosity decreases, the permeability becomes smaller, but the slope of the reduction curves increases over the decrease in porosity. The hydraulic conductivity of the drain gradually decreases when the fibre fraction is between the loose and medium ranges, but this reduction becomes sharper when fibres are denser ($n < 0.5$).

There is a clear difference between the hydraulic conductivity of jute and coir drains, as shown in Figure 9. For the same porosity, coir fibres result in an apparently higher permeability than the jute fibres. The k of the coir media decreases from 0.21 m/s at $n=0.9$ to 3.5×10^{-4} m/s at $n=0.45$, whereas the jute fibres show k decreasing from 0.015 to 4.2×10^{-6} m/s for

Figure 9. Hydraulic conductivity over porosity of jute and coir with different twisting angle

the same range of porosity. The coir fibres also resist a reduction of porosity better than jute fibres; for example, when porosity falls from 0.9 to 0.45, the k of the coir decreases by a factor of 600, but this parameter of the jute decreases by a much greater factor of 3571. This indicates the distinct advantage in hydraulic conductivity that coir fibres have over jute fibres.

The difference between the micro-characteristics of jute and coir fibres could explain the deviation in hydraulic behaviour between jute and coir drains. First, the coir fibres used in this investigation had an average diameter of 235 μm , which was much larger than that of jute – that is, $D_{f,a} = 42.0 \mu\text{m}$. As shown above, the medium composed of smaller-diameter fibres had a greater surface area, although the fibre fraction of media was constant, leading to increased friction between the fluid and the fibres. In addition, the jute fibre had a larger dispersion in size than the coir. The average value of σ_v estimated from the distribution in the diameter of the fibres (Figure 3) was 27.1 and 40.3% for coir and jute, respectively, and this indicates a much wider range in diameter of the jute fibres used in this study. This explains why jute drains had a much lower permeability than coir drains.

Moreover, a micro-observation of the cross-sectional shape of the jute and coir fibres (Figure 3) indicates that jute fibre has irregular shapes, particularly polygonal ones, whereas the coir fibre is almost round, thus having the smallest perimeter of those with the same cross-sectional area. For example, the perimeter of a square and hexagon is 1.13 and 1.05 times larger than a circular one with the same area. By referring to Equation 4, the shape factor c of jute was thus greater than that of coir. This difference in geometric features contributed to jute having a larger fluid–fibre contact area than coir, making the jute drain much lower in permeability than its counterpart.

4.3.2 Influence of the microstructure of fibre drain

In this study, two structural types of fibre drain including non-twisted and twisted fibres were investigated. The effect that the twisting angle has on the permeability of a fibre drain is shown in Figure 9, where for the same porosity, the larger the twisting angle the lower the permeability of the drain. For example, with $n = 0.5$ the non-twisted coir fibres have a hydraulic conductivity of $8.5 \times 10^{-4} \text{ m/s}$ while the fibre drains with a twisting angle of 15° and 25° have a lower hydraulic conductivity – that is, 6.1×10^{-4} and $4.8 \times 10^{-4} \text{ m/s}$, respectively. The same behaviour also occurs with jute fibres, but it is more apparent; when $n = 0.6$, the jute drain without twisting has k of $7.1 \times 10^{-5} \text{ m/s}$ but this decreases to 3.8×10^{-5} and $2.2 \times 10^{-5} \text{ m/s}$ when the jute is twisted at 15° and 25° , respectively. However, the influence that the twisting angle has on the permeability of a fibre drain is not as significant when the fibres are looser, in fact it can be ignored when $n > 0.7$ and 0.8 for both coir and jute drains.

The fibres in the non-twisted structure (Figure 1(a)) were packed randomly without twisting them around the axis of the drain, thus making porous channels along the fibres shorter than those formed in the twisted structure where the fibres created an angle to the axis of the bundle (Figure 1(b)). This difference resulted in a more complex and tortuous fluid path, and as a consequence the hydraulic conductivity of the twisted drain was smaller. Assuming that the straight length of the drain with non-twisted fibres would be the shortest distance for fluid to travel, then the fluid path in fibres twisted at angle θ was $1/\cos(\theta)$ longer than the non-twisted case, and therefore the larger twisting angle caused a greater tortuosity and resulted in lower permeability (Equation 4).

4.3.3 Comparison with other studies

The permeability of jute and coir fibres without twisting was normalised to the average diameter of the fibres and then compared with those reported by previous studies (Figure 10). To obtain this figure, a number of studies about the permeability of fibrous media are adopted, including analytical solutions such as solving the Navier–Stokes equations (Happel, 1959), modifying the KC method (Gebart, 1992), incorporating the parabolic distribution of fluid velocity into the Stokes equations (Tamayol and Bahrami, 2009), and the numerical method by coupling the finite-volume method and the discrete-element method (Nguyen and Indraratna, 2016b), as well as experimental work (Rahli *et al.*, 1997). It is clear that the differences between the results shown in Figure 10 for $n > 0.75$ are insignificant, but they quickly begin to deviate when $n < 0.7$, especially for the normalised permeability of jute and coir fibres, which become much lower than those reported from previous studies when $n < 0.5$. The experimental work carried out by Rahli *et al.* (1997) using uniform cylindrical fibres with a diameter of 150 μm is the closest to the permeability curve of the coir obtained in this study.

Figure 10. Normalised permeability of jute and coir fibres in comparison with other studies

There were several differences in the micro-characteristics of fibrous media in those studies that could clarify such a deviation in hydraulic behaviour. First, previous studies used an idealised parallel arrangement of fibres where the fluid only flowed in parallel channels, whereas the fibres in this study were not completely parallel (Figure 1). Second, the analytical and numerical models adopted in this comparison considered flow in a particular unit template of fibres, such as quadratic and hexagonal forms, whereas in this study the jute and coir fibres were packed randomly. Moreover, cylindrical fibres with circular cross-sections were used in previous works, but the fibres used in the current study, especially jute, did not have a circular cross-section. Also, the perfectly uniform fibres with only a single size ($\sigma_v = 0$) used in previous studies differed from those in the jute and coir in the current work represented above, leading to a considerable difference in their fluid–fibre contact area. The denser fibres made this deviation more apparent.

It was also noted that, although diameter-normalised permeability was used to remove any influence that the difference in the sizes of the fibre between the jute and the coir would make on the results, there was still a deviation between the permeability curves of the jute and coir, particularly as the fibres became denser ($n < 0.65$); this occurred because the differences in the shape and dispersion in size between the jute and coir fibres were still valid in this approach. Note that when natural fibres are used in practice, their shape and size vary, so that using idealised conditions with cylindrical and parallel fibres is not realistic from a geoenvironmental perspective.

4.4 Prediction of hydraulic conductivity by the KC approach

By applying the KC method described in Equation 3, the hydraulic conductivity of coir and jute drains was estimated and compared with those measured in the experimental part of

Figure 11. Prediction of hydraulic conductivity by KC method in comparison with experiment

this study (Figure 11). In this application, the average diameter $D_{f,a}$ varied slightly from 39.7 to 45.7 μm and 224 to 243 μm for jute and coir drains, respectively, over different levels of porosity, and the Kozeny constant k_k was used independently of the porosity of the drain. The prediction by the KC approach using $k_k = 10$ matches the experimental result for a coir drain having $\sigma_v = 20\%$ in the porosity range from 0.45 to 0.9 quite well; the deviation between the two approaches can be ignored in this range, but it increases when the porosity of the drain is beyond the values where the predicted k becomes much higher ($n > 0.9$) or lower ($n < 0.45$) than the experimental one. The analytical prediction is less accurate when the uniformity in the size of the fibres decreases. For $\sigma_v = 30\%$, the prediction by the KC method with $k_k = 12$ is very accurate but only for $0.55 < n < 0.90$. When the fibre drain is denser or looser, the predicted curve deviates significantly from the experimental one; in fact when $n = 0.4$, the k measured in the experiment is 1.9×10^{-4} m/s but the predicted value is much higher (i.e. 6.1×10^{-4} m/s).

Where jute drains had a wider dispersion ($\sigma_v = 40\%$) in fibre size and smaller permeability, this meant that the prediction by the KC method using a porosity-independent k_k was less accurate than for coir drains. When $k_k = 9$, the predicted curve for jute matches the experimental result for $0.63 < n < 0.95$ quite well, and then begins to deviate significantly when $n < 0.6$. The greater input of k_k enables the analytical curve to be closer to those measured by the experimental approach in the denser fibres, but is not as accurate in loose media. This limitation of the KC approach using a constant k_k over the variation of porosity meant that it was only acceptable in a certain range of porosity.

4.5 Kozeny constant k_k

To improve the accuracy of the KC method at predicting the permeability of fibrous media, a flexible Kozeny constant that

Figure 12. Variation of k_k over the porosity of drain with different micro-porous parameters: (a) structure and type of fibres, (b) size of fibres, (c) uniformity of fibres, (d) in comparison to other studies

is functional for the micro-characteristics of the fibre drain must be used. The dependence of k_k on particular micro-parameters such as porosity, the structure of drains (non-twisted and twisted fibres) and the size and uniformity in the size of fibres was back-analysed on the basis of the experimental results represented in previous sections and is shown in Figure 12. Figure 12(a) shows how k_k varies over the different porosities of drains for non-twisted and twisted fibres, including jute and coir. The variation of k_k for non-twisted fibres is insignificant, particularly from 6 to 10 with a range of porosity of $0.65 < n < 0.9$. The difference between the k_k of jute and coir is not evident in this range, but k_k increases rapidly and the deviation between jute and coir becomes more apparent when the medium is denser or looser. At $n = 0.45$, k_k reaches almost 30 for coir and 80 for jute. Moreover, the influence of the drain structure (twisted and non-twisted fibres) on k_k can be ignored for loose fibres but increases considerably as the porosity decreases; in fact the gaps between the k_k of non-twisted and twisted fibres are completely different when n is < 0.6 for coir and 0.75 for jute.

The influence of fibre size on k_k is shown in Figure 12(b). Note that in this investigation, the uniformity of fibres was almost the same and had an insignificant influence on the results. It is interesting that the effect of fibre size on k_k is not consistent over the variation of porosity, for example, when $n > 0.64$, the biggest diameter fibres have the highest values of k_k , but this trend becomes opposite when $n < 0.64$. The figure also indicates that the three curves of k_k all show their bottom at different degrees of porosity, depending on the size of fibres. The k_k of the smaller fibres reaches the bottom at a larger porosity (e.g. 0.77 for $D_{f,a} = 376 \mu\text{m}$ and 0.43 for $D_{f,a} = 155 \mu\text{m}$), and with a sharper drop, but the influence of fibre size on k_k only becomes critical when the fibre fraction enters the dense zone (i.e. $n < 0.5$).

There is an apparent contribution by the dispersion in the size of fibre to the value of k_k as shown in Figure 12(c). As more uniform fibres are created in the drain, a more stable and lower value of k_k is obtained, in fact the fibre drain with $\sigma_v = 10\%$ shows its k_k decreasing quickly from almost 17 to

around 3 as porosity decreases from 0.93 to 0.72, but it does not change much in the denser fibres. However, a wider range of fibre sizes makes the k_k vary more, for example, with the least uniform fibres ($\sigma_v = 30\%$), k_k increases continuously from 7 at $n = 0.85$ to 60 at $n = 0.35$, and the k_k curve also reaches a lower bottom as fibres are more uniform. The minimum value of k_k increases from 2.8 to 5.1 and 7 when the uniformity declines from $\sigma_v = 10\%$ to 20 and 30%, respectively.

A number of studies (Choi *et al.*, 1998; Kyan *et al.*, 1970; Rahli *et al.*, 1997; Sullivan, 1942) have investigated the relationship between k_k and porosity for longitudinal flow through a fibrous media. Kyan *et al.* (1970) and Sullivan (1942) have shown that k_k decreases sharply as the porosity decreases from a very loose to a medium state ($n > 0.85$), and then stabilises in the medium to dense range ($0.45 < n < 0.8$). Choi *et al.* (1998) and Rahli *et al.* (1997) also found that k_k increases rapidly when the porosity turns into the very dense fibre zone ($n < 0.35$). Other studies (Gebart, 1992; Gutowski *et al.*, 1987) have adopted smaller constant values of k_k (i.e. from 1 to 2.5) for flow along parallel homogeneous fibres. Those findings were made under the same condition of fibres being highly to totally uniform ($\sigma_v = 0$) and ideally arranged in parallel. As Figures 12(c) and 12(d) show, the current k_k for fibres with a high uniformity ($\sigma_v = 10\%$) agrees with those reported in previous works. This comparison reinforces the finding in this study that more uniform fibres result in smaller values of k_k that are stable in the range from medium to dense fibres ($0.4 < n < 0.8$).

5. Conclusions

An intensive laboratory investigation into the influence of the micro-features of natural fibre drains on hydraulic conductivity was carried out in this study. Jute and coir were used to create fibre drains that were then subjected to hydraulic conductivity testing. A number of governing micro-parameters such as the shape, size and the twisting feature of fibres were investigated, and the following conclusions can be drawn.

- The drain made from larger fibres that generated a smaller fluid–fibre contact area had a higher hydraulic conductivity. Coir having a larger average diameter ($D_{f,a} = 235 \mu\text{m}$) compared with jute ($D_{f,a} = 41.8 \mu\text{m}$) resulted in a significantly greater hydraulic conductivity for the same porosity.
- The more uniform the fibre was in size, the greater was the hydraulic conductivity. For the same porosity ($n = 0.45$) and average diameter ($D_{f,a} = 235 \mu\text{m}$), the hydraulic conductivity of the coir drain decreased from 2.1×10^{-3} to 0.39×10^{-3} m/s as the uniformity of fibre decreased from $\sigma_v = 10$ to 30%, respectively. Generally jute had a larger size dispersion ($\sigma_v = 40.3\%$) than coir ($\sigma_v = 27.1\%$), leading to its lower hydraulic conductivity.
- The cross-sectional shape of jute was almost polygonal, whereas that of coir was nearly round, which meant

that jute had a larger shape factor that created a larger fluid–fibre contact area, and as a consequence, jute drains were less permeable than coir drains.

- Twisting fibres made fluid flow in the drain more complex and increased its tortuosity; for example, the hydraulic conductivity of the drain with a 25° twisting angle was more than 30% lower than the drain without twisting in a certain range of porosity (i.e. $n < 0.7$ for coir and $n < 0.8$ for jute).
- The analytical KC approach using a porosity-independent constant k_k showed an acceptable degree of accuracy at predicting the hydraulic conductivity of natural fibres (jute and coir) in a certain range of porosity, but this acceptable range of porosity decreased with a larger k_k when fibres were less uniform. The KC method, in particular, was valid for a coir drain in the porosity range: 0.45–0.9 with $k_k = 10$ and $\sigma_v = 20\%$; 0.55–0.9 with $k_k = 12$ and $\sigma_v = 30\%$, and for a jute drain in a porosity range from 0.63 to 0.95 with $k_k = 9$ and $\sigma_v = 40\%$.
- The micro-features of fibrous media such as porosity, size, the uniformity of fibres and the arrangement of fibres in a drain (non-twisted and twisted fibres) had a significant influence on the Kozeny constant k_k . Generally, k_k decreased to a minimum level before increasing continuously while the porosity of the drain decreased from 0.95 to 0.3. Fibres that were twisted more resulted in a larger magnitude of k_k , while fibres with a higher uniformity led to a much lower and more stable value of k_k (e.g. 3–4 with $\sigma_v = 10\%$ for coir drain).

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REFERENCES

- Akagi T (1994) Hydraulic application of geosynthetics to filtration and drainage problem – with special reference to prefabricated band-shaped drains. In *Proceedings of the 5th International Conference on Geotextiles and Geomembranes and Related Products, Singapore* (Karunaratne GP, Chew SH and Wong KS (eds)). SEAC-IGS, pp. 99–110.
- Ali M (2010) Coconut fibre – a versatile material and its applications in engineering. In *Proceedings of the 2nd International Conference on Sustainable Construction Materials and Technologies, Ancona, Italy* (Zachar J, Claisse P, Naik TR and Ganjian E (eds)). UWM Center for By-Products Utilization, Milwaukee, WI, USA, pp. 1441–1454.
- Arulrajah A, Abdullah A, Bo MW and Bouazza A (2009) Ground improvement techniques for railway embankments. *Ground Improvement* **162**(1): 3–14, <http://dx.doi.org/10.1680/grim.2009.162.1.3>.
- Asha BS and Mandal JN (2012) Absorption and discharge capacity tests on natural prefabricated vertical drains. *Geosynthetics International* **19**(4): 263–271, <http://dx.doi.org/10.1680/gein.12.00013>.

- Asha BS and Mandal JN (2015) Laboratory performance tests on natural prefabricated vertical drains in marine clay. *Proceedings of the Institution of Civil Engineers – Ground Improvement* **168**(1): 45–65, <http://dx.doi.org/10.1680/grim.13.00001>.
- ASTM (2008) D 4716: Standard test method for constant head hydraulic transmissivity (in-plane flow) of geotextiles and geotextile related products. ASTM International, West Conshohocken, PA, USA.
- Babu GLS and Vasudevan AK (2007) Evaluation of strength and stiffness response of coir-fibre-reinforced soil. *Proceedings of the Institution of Civil Engineers – Ground Improvement* **11**(3): 111–116, <http://dx.doi.org/10.1680/grim.2007.11.3.111>.
- Beena KS and Babu KK (2008) Testing coir geotextile drains for soft ground improvement. *Proceedings of the Institution of Civil Engineers – Ground Improvement* **161**(1): 43–49, <http://dx.doi.org/10.1680/grim.2008.161.1.43>.
- Carman PC (1937) Fluid flow through granular beds. *Chemical Engineering Research and Design* **75**: S32–S48, [http://dx.doi.org/10.1016/S0263-8762\(97\)80003-2](http://dx.doi.org/10.1016/S0263-8762(97)80003-2).
- Choi MA, Lee MH, Chang J and Lee SJ (1998) Permeability modelling of fibrous media in composite processing. *Journal of Non-Newtonian Fluid Mechanics* **79**(2–3): 585–598.
- Chu J, Bo MW and Choa V (2004) Practical considerations for using vertical drains in soil improvement projects. *Geotextiles and Geomembranes* **22**(1–2): 101–117.
- Chu J, Bo MW and Arulrajah A (2009) Reclamation of a slurry pond in Singapore. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering* **162**(1): 13–20, <http://dx.doi.org/10.1680/geng.2009.162.1.13>.
- Defoirdt N, Biswas S, Vriese LD et al. (2010) Assessment of the tensile properties of coir, bamboo and jute fibre. *Composites Part A* **41**(5): 588–595.
- Gebart BR (1992) Permeability of unidirectional reinforcements for RTM. *Journal of Composite Materials* **26**(8): 1100–1133.
- Gregory MR and Andradý AL (2003) Plastic in the marine environment. In *Plastics and Environment* (Andradý AL (ed.)). John Wiley & Sons, Hoboken, NJ, USA, pp. 379–401.
- Gupta KM (2011) Starch based composites for packing applications. In *Handbook of Bioplastics and Biocomposites Engineering Applications* (Pilla S (ed.)). John Wiley & Sons, Hoboken, NJ, USA, pp. 189–262.
- Gutowski TG, Cai Z, Bauer S et al. (1987) Consolidation experiment for laminate composites. *Journal of Composite Materials* **21**(7): 650–699.
- Happel J (1959) Viscous flow relative to arrays of cylinders. *AIChE Journal* **5**(2): 174–177.
- Indraratna B, Rujikiatkamjorn C, Kelly C and Buys H (2012) Soft soil foundation improved by vacuum and surcharge loading. *Proceedings of the Institution of Civil Engineers – Ground Improvement* **165**(2): 87–96, <http://dx.doi.org/10.1680/grim.10.00032>.
- Indraratna B, Nguyen TT, Carter J and Rujikiatkamjorn C (2016) Influence of biodegradable natural fibre drains on the radial consolidation of soft soil. *Computers and Geotechnics* **78**: 171–180, <https://doi.org/10.1016/j.compgeo.2016.05.013>.
- Kelly R (2014) Assessment of smear parameters for use in wick drain design. *Proceedings of the Institution of Civil Engineers – Ground Improvement* **167**(3): 186–191, <http://dx.doi.org/10.1680/grim.13.00007>.
- Kim JH and Cho SD (2008) Pilot scale field test for natural fiber drain. In *Proceedings of the 4th Asian Regional Conference on Geosynthetics* (Li G, Chen Y and Tang X (eds)). Springer-Verlag, Berlin/Heidelberg, Shanghai, China, pp. 409–414.
- Kim YW, Park JY and Jang YS (2001) Consolidation efficiency of natural and plastic geosynthetic band drains. *Geosynthetics International* **8**(4): 283, <http://dx.doi.org/10.1680/gein.8.0196>.
- Kozeny J (1927) Ueber kapillare Leitung des Wassers im Boden. *Akademie der Wissenschaften in Wien, Sitzungsberichte* **136**(2a): 271–306 (in German).
- Kyan CP, Wasan DT and Kintner RC (1970) Flow of single-phase fluids through fibrous beds. *Industrial and Engineering Chemistry Fundamentals* **9**(4): 596–603.
- Lee SL, Karunaratne GP, Ramaswamy SD, Aziz MA and Das Gupta NC (1994) Natural geosynthetic drain for soil improvement. *Geotextiles and Geomembranes* **13**(6–7): 457–474.
- Li J and Gu Y (2005) Coalescence of oil-in-water emulsions in fibrous and granular beds. *Separation and Purification Technology* **42**(1): 1–13.
- Massey B and Ward-Smith J (2006) *Mechanics of Fluids*, 8th edn. Taylor & Francis, New York, NY, USA.
- Midha VK, Kumar SS and Sharma A (2014) Performance of transesterified jute rolled erosion-control products. *Geosynthetics International* **21**(5): 301–309, <http://dx.doi.org/10.1680/gein.14.00017>.
- Nakayama A, Kuwahara F and Sano Y (2007) Concept of equivalent diameter for heat and fluid flow in porous media. *AIChE Journal* **53**(3): 732–736.
- Nguyen TT and Indraratna B (2016a) Experimental and numerical investigations into hydraulic behaviour of coir fibre drain. *Canadian Geotechnical Journal* **54**(1): 75–87.
- Nguyen TT and Indraratna B (2016b) Hydraulic behaviour of parallel fibres under longitudinal flow: a numerical treatment. *Canadian Geotechnical Journal* **53**(7): 1081–1092.
- Nicholson JW (2006) *The Chemistry of Polymers*, 3rd edn. The Royal Society of Chemistry, Cambridge, UK.
- Ozgunmus T, Mobedi M and Ozkol U (2014) Determination of Kozeny constant based on porosity and pore to throat size ratio in porous medium with rectangular rods. *Engineering Applications of Computational Fluid Mechanics* **8**(2): 308–318.
- Rahli O, Tadrist L, Miscevic M and Santini R (1997) Fluid flow through randomly packed monodisperse fibers: the Kozeny–Carman parameter analysis. *ASME Journal of Fluids Engineering* **119**(1): 188–192.
- Rahman MS (2010) Jute – a versatile natural fibre. Cultivation, extraction and processing. In *Industrial Applications of Natural Fibres: Structure, Properties and Technical Applications* (Mussig J (ed.)). John Wiley and Sons, Ltd, Chichester, UK, pp. 135–161.
- Rasband WS (2014) *ImageJ*. US National Institutes of Health, Bethesda, MD, USA. See <http://imagej.nih.gov/ij/> (accessed 25/04/2017).
- Rawes BC (1997) Critical parameters for specification of prefabricated vertical drains. *Geosynthetics International* **4**(1): 51–64, <http://dx.doi.org/10.1680/gein.4.0088>.
- Rodriguez E, Giacomelli F and Vazquez A (2004) Permeability–porosity relationship in RTM for different fibreglass and natural reinforcement. *Journal of Composite Materials* **38**(3): 259–268.
- Saha P, Roy D, Manna S et al. (2012) Durability of transesterified jute geotextiles. *Geotextiles and Geomembranes* **35**: 69–75, <https://doi.org/10.1016/j.geotextmem.2012.07.003>.
- Sharma S and Siginer DA (2010) Permeability measurement methods in porous media of fiber reinforced composites. *Applied Mechanics Reviews* **63**(2): 02080201–02080219.
- Som N, Chattopadhyay BC and Sanyal T (2009) *A Manual on Use of Jute Geotextiles in Civil Engineering*, 4th edn. Jute Manufacturers Development Council, Kolkata, India.
- Subaida EA, Chandrakaran S and Sankar N (2009) Laboratory performance of unpaved roads reinforced with woven coir geotextiles. *Geotextiles and Geomembranes* **27**(3): 204–210.

- Sullivan RR (1942) Specific surface measurements on compact bundles of parallel fibers. *Journal of Applied Physics* **13**(11): 725–730.
- Tamayol A and Bahrami M (2009) Analytical determination of viscous permeability of fibrous porous media. *International Journal of Heat and Mass Transfer* **52**(9–10): 2407–2414.
- Venkatappa Rao G, Sampath Kumar JP and Banerjee PK (2000) Characterization of a braided strip drain with coir and jute yarns. *Geotextiles and Geomembranes* **18**(6): 367–384.
- Vinod P and Bhaskar AB (2012) Model studies on woven coir geotextile-reinforced sand bed. *Proceedings of the Institution of Civil Engineers – Ground Improvement* **165**(1): 53–57, <http://dx.doi.org/10.1680/grim.9.00030>.
- Vinod P and Minu M (2010) Use of coir geotextiles in unpaved road construction. *Geosynthetics International* **17**(4): 220–227, <http://dx.doi.org/10.1680/gein.2010.17.4.220>.
- Williams JG, Morris CEM and Ennis BC (1974) Liquid flow through aligned fiber beds. *Polymer Engineering and Science* **14**(6): 413–419.
- Xu P and Yu B (2008) Developing a new form of permeability and Kozeny–Carmen constant for homogeneous porous media by means of fractal geometry. *Advances in Water Resources* **31**(1): 74–81.
- Yazdchi K, Srivastava S and Luding S (2012) Micro–macro relations for flow through random arrays of cylinders. *Composite Part A: Applied Science and Manufacturing* **43**(11): 2007–2020.
- Yin JH (1997) A nonlinear model of geosynthetic-reinforced granular fill over soft soil. *Geosynthetics International* **4**(5): 523–537, <http://dx.doi.org/10.1680/gein.4.0105>.
- Zhan C and Yin JH (2001) Elastic analysis of soil–geosynthetic interaction. *Geosynthetics International* **8**(1): 27–48, <http://dx.doi.org/10.1680/gein.8.0185>.

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