ELSEVIER
CrossMark
Procedia Engineering
Volume 143, 2016, Pages 1218–1225
Advances in Transportation Geotechnics 3 . The 3rd International Conference on Transportation Geotechnics (ICTG 2016)
Procedia Engineering

Development of Smart Braided Structures for Sensing of Geotechnical Structures

Sohel Rana[1*], Raul Fangueiro[1] and Antonio Gomes Correia[2]

[1] *Fibrous Materials Research Group, University of Minho, 4800-058 Guimarães, Portugal.*

[2] *Department of Civil Engineering, University of Minho, 4800-058 Guimarães, Portugal.*

soheliitd2005@gmail.com, rfangueiro@civil.uminho.pt, agc@civil.uminho.pt

Abstract

This paper reports the development of innovative tri-axial braided structures for strain and damage sensing of geotechnical structures. These innovative braided structures have been developed through braiding of polyester multi-filaments over an axial core composed of mixture of conductive (carbon) and non-conductive (glass) fibres. It was observed that the developed structures were capable of self-monitoring of strain and damage and tailoring the composition of core fibres resulted in excellent sensing of low strain in continuous manner with gauge factor as high as 23. It was further observed that the mechanical performance and surface roughness (which controls their adhesion with soils) could be easily tailored through adjustment of core and sheath component's parameters, respectively. Furthermore, a self-sensing epoxy matrix containing uniformly distributed short carbon fibres was developed in order to combine with the developed braided structures (through impregnation using a special technique) and to further enhance their self-sensing capability. The results discussed in this paper depict that these tailorable and innovative braided structures can be advantageously applied in geotechnical structures for sensing purposes.

Keywords: Braided structures, Self-monitoring, Tailorability, Geotechnical applications

1 Introduction

Braiding is an old textile technology known for producing ropes and shoe laces. However, braided structures and composites present a number of attractive characteristics such as high shear and torsional strength and stiffness, enhanced transverse strength and modulus, high damage tolerance and fatigue life, notch insensitivity, high fracture toughness, complex shapes, etc. and due to these reasons, braided structures and composites are being extensively utilized in different technical sectors including medical, transportation, aerospace engineering, sports, among others (Rana, 2015).

[*] Corresponding author

 Selection and peer-review under responsibility of the Scientific Programme Committee of ICTG 2016

doi:10.1016/j.proeng.2016.06.106

In geotechnical engineering, reinforcement of soil is required to improve various properties of soils such as stability, bearing capacity, reduction of settlements and lateral deformation. Different methods have been tried to reinforce problematic soils such as physical (vibration, thermo-electrical, freeze and thaw, etc.), mechanical (using fibrous materials, compaction, etc.) and chemical methods (cement, lime, bitumen, enzymes, polymeric resins, etc.) (Hejazi, 2012).

Recently, different types of fibrous materials including natural and synthetic fibres in various forms such as woven and non-woven geotextiles, bars, strips, grids, etc. or short fibres have been utilized to improve the stability of low strength fine and granular soils. In continuous form, fibres are used to stabilize the slopes and protect them from erosion, and the discrete fibres are used to improve the bearing capacity of soils for wall retention, slope protection, reinforcement of embankments, and many other purposes (Hejazi 2012, Palmeira et al., 2008). Fibre reinforced polymer composites (FRPs), especially those fabricated using thermosetting resins provide high strength and stiffness and low creep, which are essential properties for geotechnical applications. Additionally, FRPs can be made self-sensing by tailoring their composition and structure. Self-sensing FRPs can sense strain and damages induced in their structure as well as in the reinforced soils through change in the electrical resistance. Therefore, these smart FRPs can be highly useful for the geotechnical structures, in order to perform timely maintenance and avoid sudden collapse.

In this paper, the production and properties of braided structures and composites have been discussed and their potential for application in geotechnical engineering has been highlighted. The possibility to tailor mechanical properties, surface texture and strain sensing behaviour of braided composites has also been discussed.

2 Production of Braided Structures and Composites

Braided structures are produced through different types of two dimensional and three dimensional braiding techniques. For industrial applications, tri-axial braided structures have been used extensively (Rana, 2015). In tri-axial braided structures, one set of yarns, known as axial yarns or core yarns, are introduced in the axial direction and the other two sets of yarns are braided around the straight axial yarns. As the axial yarns are oriented along the axis of the braided structure, they strongly influence the mechanical properties. Figure 1a shows the production of a tri-axial braided structure. The step involving the impregnation of axial yarns with polymeric resin is used to produce braided composites.

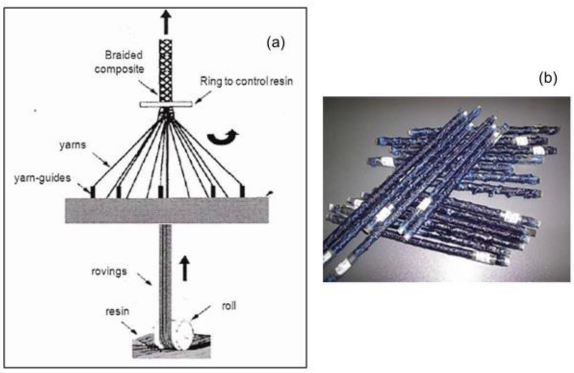

Figure 1: (a) Production of braided structures and composites and (b) produced braided rods (Fangueiro, 2013)

There also exist different techniques for producing braided composites. In case of thermo-setting matrices, braided structures can be impregnated with polymeric resin through resin transfer moulding (RTM). Another simple approach of fabricating tri-axial braided composites is to pass the axial fibre through a resin bath prior to the braiding machine, as shown in Figure 1a. The braided structures after consolidation through the braiding process and subsequent curing (not shown in Figure 1) becomes circular braided composites, known as braided composite rods or BCR, as shown in Figure 1b.

In case of thermo-plastic matrix, one set of thermoplastic yarns can be introduced as axial yarns into the braided structure. The thermoplastic yarns can be subsequently melted and consolidated using a heated die (e.g. pultrusion die) to form the matrix of the composite (Rana, 2015). The thermoplastic yarns can also be blended with other type of reinforcing yarns to produce tri-axial braided composites.

3 Mechanical Properties of Braided Composites

Mechanical properties of tri-axial braided structures and composites are highly dependent on the properties of the axial yarns. The tensile load-elongation curves of tri-axial braided structures show three distinct phases. At very low strain, straightening of crimps present in the axial yarns takes pace (phase I), followed by complete take up of load by the axial yarns (phase II) and transfer of load to the braided yarns, after the breakage of axial yarns (phase III). It is obvious that the second phase is the main load bearing stage during the deformation of braided structure. The tensile properties of braided composites with different types of axial fibres and matrix are provided in Table 1 (Fangueiro, 2013; Kling, 2013).

Core Composition	Type of matrix	Fibre mass (%)	Tensile strength (MPa)	Elastic modulus (GPa)
100% G*	Polyester	41	485	55
77% G, 23% C*	Polyester	35	767	78
53% G, 47% C	Polyester	32	740	74
100% C	Polyester	33	748	96
50% G, 45% C, 5% HT PE*	Polyester	35	679	84
52% G, 45% C, 3% HT PE	Polyester	33	653	81
75% G, 22% C, 3% HT PE	Polyester	34	691	73
100% G	PP*	60	159	6.5
100% G	PP	70	185	8.2
100% G	PP	80	208	9.1
**100% G	PP	60	760	29.5

*G- Glass, C- Carbon, HT PE- High tenacity polyethylene, PP- Polypropylene
** Glass/polypropylene composite produced from commercial Twintex® roving

Table 1: Tensile strength and elastic moduli of thermosetting and thermoplastic BCR

It can be noticed that the tensile properties of braided composites strongly depend on the composition of axial yarns. The use of carbon fibres results in very high elastic modulus as well as tensile strength of braided composites. Combination of carbon with glass or HTPE (high tenacity polyethylene) does not alter the tensile strength significantly; however, reduces the elastic modulus considerably. Also, the use of thermoplastic matrix such as polypropylene (PP) reduces the elastic modulus, but does not affect tensile strength, if the axial fibres are distributed uniformly and the matrix is well consolidated. Braided composites produced using commercial Twintex® roving, in which the reinforcing fibres are well blended using comingling process, shows good tensile properties. However, the tensile properties of other thermoplastic composites listed in Table 1, in which the axial yarns are mixed using a laboratory scale blending process, are much inferior. Non-uniform distribution of axial yarns and presence of voids are the main reasons behind their inferior mechanical properties. Consolidation of matrix is also a vital step in case of thermoplastic braided composites, as improper consolidation can significantly affect the mechanical properties. Therefore, the parameters of the consolidation process (e.g. design of die, temperature profile, pressure, etc.) should be optimized.

4 Surface Properties of Braided Composites

One distinct advantage of braided structures and composites for reinforcing soils and other matrices is their textured surface. This can strongly influence the interface between braided structures and matrix and consequently, their reinforcing capability. The textured surface of braided structures results in mechanical interlocking with the matrix and results in better interface and enhanced mechanical performance. The surface texture of braided structures or composites can be very easily tailored just varying the parameters of the production process (Cunha, 2014). Figures 2a to 2d show different types of surface geometry obtained by varying the braiding speed and using different types of braiding yarns. The distance between the surface ribs (D) depends strongly on the braiding speed and on the use of one or more braided (or coarser) yarns, instead of simple monofilament yarns, for the braiding purpose (i.e. outer yarns). It has been observed that the geometry (Fig. 2c) produced using high speed and 2 braided yarns in the outer layer showed higher distance between the ribs and excellent bonding with the surrounding matrix. It was possible to fully utilize the tensile strength of the braided rods prior to debonding with the matrix. Therefore, it is possible to tailor easily the surface texture of braided structures and consequently, their interface with soils for different geotechnical applications.

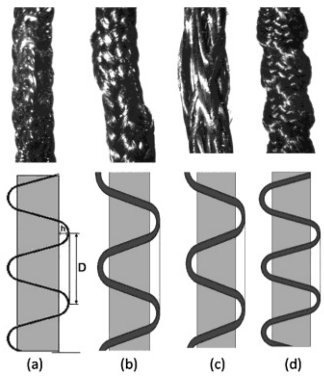

Figure 2: Surface geometry of braided rods produced with: (a) 16 simple braiding yarns at 0.54 m/min, (b) 1 braided yarn and 15 simple braiding yarn at 0.54 m/min (c) 2 braided yarns and 14 simple braiding yarns at 1.07 m/min and (d) 2 braided yarns and 14 simple braiding yarns at 0.54 m/min (Cunha, 2014)

5 Sensing Behaviour of Braided Composites

Self-sensing composites can be highly useful for geotechnical applications to detect damages in the reinforcing system or structure, in order to perform timely maintenance. This can help to avoid high maintenance cost due to complete collapse of the structures and to avoid accidents causing loss of human lives and money. Tri-axial braided composites offer the possibility to fabricate smart reinforcing systems for soils. A hybrid core containing electrically conducting carbon fibres and other non-conducting fibres like glass, aramid, etc, can introduce strain and damage sensing capability to the braided structures (Rana, 2014). As compared to some previous attempts of fabricating smart braided composites using optical sensors, this approach is simple low cost and the sensing system is more robust and suitable for geotechnical applications.

Figure 3 and Table 2 show the strain sensing behaviour of BCR with different core compositions. It has been observed that the sensing behaviour improves with the decrease in carbon content, however, at the cost of reduced mechanical properties. BCR with 23% carbon fibres results in a gauge factor (fractional change in resistance per unit strain) of 23.4 during flexural deformation. Additionally, the strain sensing behavior of BCR is quite reversible making them suitable for continuous strain monitoring of reinforced soil structures. The change in electrical contact points during deformation or breakage of axial fibres is the main reason behind the strain and damage sensing behavior of braided composites. Higher change in electrical contact points due to overall less number of electrical contacts in braided composites containing lower amount of carbon fibres results in higher change in electrical resistance and better self-sensing behaviour.

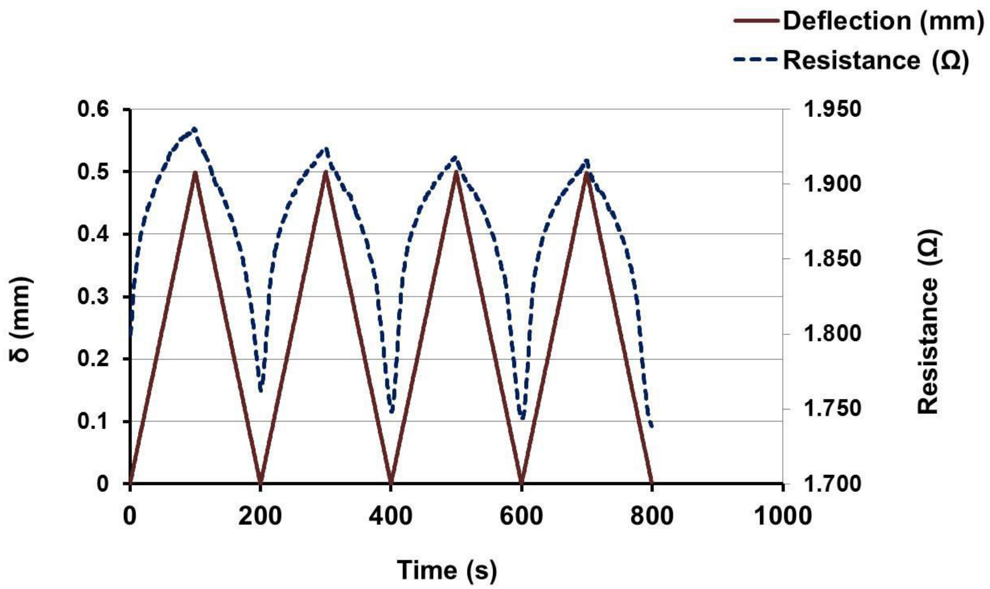

Figure 3: Piezoresistive behavior of BCR (Rana, 2014)

Cycles	1		2		3		4		Average GF*
BCR type	ε* (× 10^{-2})	ΔR/R*	ε (× 10^{-2})	ΔR/R	ε (×10^{-2})	ΔR/R	ε (× 10^{-2})	ΔR/R	
23% C*	0.48	0.10	0.48	0.11	0.48	0.12	0.48	0.12	23.4
47% C	0.48	0.04	0.48	0.02	0.48	0.01	0.48	0.01	4.2
100% C	0.55	0.02	0.55	0.01	0.55	0.01	0.55	0.01	2.3

*C- Carbon, ε- Strain, ΔR/ R- Fractional change in resistance, GF- Gauge factor

Table 2: Fractional resistance change and average gauge factor of BCRs (Rana, 2014)

6 Self-sensing Matrix System

Development of self-sensing matrix is another approach of enhancing sensing behaviour of braided composites. Recently, multi-scale braided composites containing dispersed carbon nanotubes (CNTs) within the matrix showed the possibility to detect micro-scale damages (Rana, 2015). However, high cost and dispersion problems are the main challenges for fabricating CNT based multi-scale composites. Another approach of developing self-sensing matrix is through dispersion of chopped carbon fibres with lengths ranging from 1mm to 3mm (Rosado, 2013). These short carbon fibres can be easily mixed with the resin using simple mixing process and can be distributed quite homogeneously within the matrix, as shown in Figure 4. The developed carbon fibre dispersed matrix shows very good strain sensing behavior under both monotonic and cyclic loading, as can be noticed from Table 3 and Figure 4. An average gauge factor of 47 can be achieved by dispersing 0.5% chopped carbon fibres (3 mm) at 1.8% strain level.

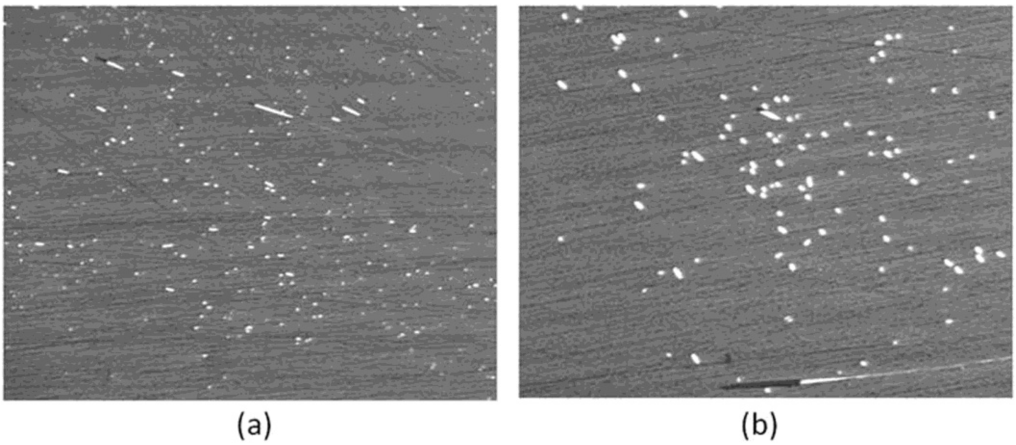

Figure 4: Distribution of chopped fibres of 1 mm length within the matrix at 0.5% concentration

Cycle No.	1		2		3		
Conc. of chopped fibre	ε	ΔR/ R	ε	ΔR/ R	ε	ΔR/ R	Average GF
0.5%	1.8	78.09	1.8	86.61	1.8	89.03	47
0.75%	1.8	67.73	1.8	83.77	1.8	88.31	44
1.25%	1.8	73.83	1.8	84.83	1.8	88.47	46

Table 3: Fractional change in resistance and average gauge factors of chopped fibre dispersed matrix (Rosado, 2013)

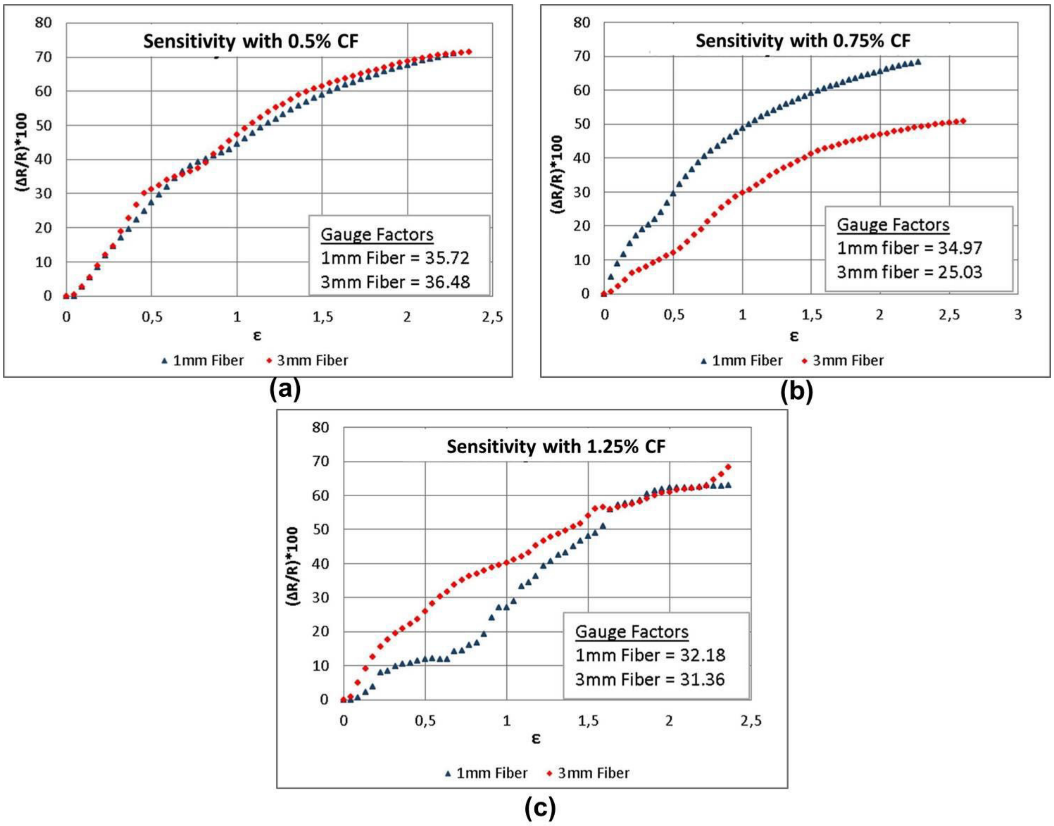

Figure 5: Variation of fractional resistivity of chopped fibres dispersed matrix with compressive strain at different concentrations: (a) 0.5%, (b) 0.75% and (c) 1.25% (Rosado, 2013)

7 Conclusions

From the results presented in this paper, it can be concluded that braided structures and composites possess tailor-able mechanical, surface and sensing behaviors. The developed braided composites with optimum composition showed excellent low strain sensitivity with gauge factor as high as 23 under cyclic flexural loading. Due to these attractive features, they can be promising reinforcing materials for soils in different geotechnical applications. Additionally, braided structures can also be prepared highly resistant to chemical degradation, which is an important requirement for geotechnical applications. The use of chemical resistant braiding fibres such as polyester, PP, etc. can protect the inner axial fibres and provide high chemical resistance. Also, braided composites fabricated using thermosetting resins show low creep and time-dependent behaviours, which are also essential for geotechnical applications. Although braided composites with thermoplastic matrix show high level of creep, their creep behaviour can be significantly improved by developing multi-scale braided composites with dispersed nanoparticles (nano TiO_2, SiO_2, etc.) within the matrix. Future research attempts are required to investigate various properties of soils reinforced with smart braided structures and composites.

References

Cunha, F., Rana, S., Fangueiro, R., & Vasconcelos, G. (2014). Excellent bonding behaviour of novel surface-tailored fibre composite rods with cementitious matrix. Bulletin of Materials Science, 37(5), 1013-1016.

Fangueiro, R., Rana, S., & Gomes, C. (2013). Braided composite rods: innovative fibrous materials for geotechnical applications. Geomechanics and Engineering, 5(2), 87-97.

Hejazi, S. M., Sheikhzadeh, M., Abtahi, S. M. and Zadhoush, A. (2012), "A simple review of soil reinforcement by using natural and synthetic fibers", Constr. Build. Mater., 30, 100–116.

Kling, V., Rana, S., & Fangueiro, R. (2013, January). Fibre Reinforced Thermoplastic Composite Rods. In Materials Science Forum (Vol. 730, pp. 331-336).

Palmeira, E., Tatsuoka, F., Bathurst, R., Stevenson, P. and Zornberg, J. (2008), "Advances in Geosynthetics Materials and Applications for Soil Reinforcement and Environmental Protection Works", EJGE Special Volume Bouquet, 08, 38.

Rana, S., & Fangueiro, R. (Eds.). (2015). Braided Structures and Composites: Production, Properties, Mechanics, and Technical Applications (Vol. 3). CRC Press.

Rana, S., Zdraveva, E., Pereira, C., Fangueiro, R., & Correia, A. G. (2014). Development of Hybrid Braided Composite Rods for Reinforcement and Health Monitoring of Structures. The Scientific World Journal.

Rosado Mérida, K. P., Rana, S., Gonilho-Pereira, C., & Fangueiro, R. (2013, January). Self-Sensing Hybrid Composite Rod with Braided Reinforcement for Structural Health Monitoring. In Materials Science Forum (Vol. 730, pp. 379-384).