Geomechanics and Engineering, Vol. 5, No. 2 (2013) 87-97 87
DOI: http://dx.doi.org/10.12989/gae.2013.5.2.087

Braided composite rods: Innovative fibrous materials for geotechnical applications

Raul Fangueiro*[1,3], Sohel Rana[1] and A. Gomes Correia[1,2]

[1]*Department of Civil Engineering, University of Minho, 4800-058 Guimarães, Portugal*
[2]*CTAC – Territory, Environment and Construction Research Centre, University of Minho, 4800-058 Guimarães, Portugal*
[3]*Center for Textile Science and Technology, University of Minho, 4800-058 Guimarães, Portugal*

(Received August 16, 2012, Revised December 18, 2012, Accepted December 20, 2012)

Abstract. In this paper, a novel fibrous material known as axially reinforced braided composite rods (BCRs) have been developed for reinforcement of soils. These innovative materials consist of an axial reinforcement system, comprised of longitudinally oriented core fibres, which is responsible for mechanical performance and, a braided cover, which gives a ribbed surface texture for better interfacial interactions with soils. BCRs were produced using both thermosetting (unsaturated polyester) and thermoplastic (polypropylene) matrices and synthetic (carbon, glass, HT polyethylene), as well as natural (sisal) core fibres. BCRs were characterized for tensile properties and the influence of core fibres was studied. Moreover, BCRs containing carbon fibre in the core composition were characterized for piezoresistivity and strain sensing properties under flexural deformation. According to the experimental results, the developed braided composites showed tailorable and wide range of mechanical properties, depending on the core fibres and exhibited very good strain sensing behavior.

Keywords: fibrous materials; braided rods; mechanical properties; sensing behaviour; soil reinforcement

1. Introduction

Soil reinforcement is a method of improving properties (stability, bearing capacity, reduction of settlements and lateral deformation) of problematic soils using various additives (Binici 2005, Yarbasi 2007, Prabakar 2004). Different routes of soil reinforcement including physical (vibration, thermo-electrical, freeze and thaw, etc.), mechanical (using fibrous materials, compaction, etc.) and chemical methods (cement, lime, bitumen, enzymes, polymeric resins, etc.) are already existing (Hejazi 2012). However, many of these techniques are either ineffective or expensive and, therefore finding new low cost and efficient soil reinforcement techniques is the primary motivation of research and development in this area.

In geotechnical engineering, recently several researchers have utilized different fibres, including natural fibres and/or synthetics, for reinforcing problematic soils specially for increasing shear strength of low strength granular and fine soils (Hejazi 2012, Palmeira *et al*. 2008). In fact,

*Corresponding author, Professor, E-mail: rfangueiro@civil.uminho.pt

fibres can be used for reinforcing soils either in continuous insert form (sheets like woven or and non-woven geotextiles, strips, bars and grids) or as randomly oriented discrete inclusions. The first method was used mostly in slope stabilization of soils to prevent slopes from erosion or shallow failure, while the second in soil reinforcement in general terms for improving bearing capacity in various applications ranging from retaining walls and slope protections, reinforcement of embankments, and enhancement of the bearing capacity of footings and pavements. Various natural fibres such as sisal, coir, palm, jute, bamboo, flax, cane, etc. and synthetic fibres like polypropylene, polyethylene, polyester, nylon, glass, steel, etc. have been utilized for soil reinforcement purposes.

Fibre reinforced polymers (FRPs) have been developed and applied for soil reinforcement purposes, due to their high tensile strength, stiffness, impact resistance and durability with respect to soil chemistry and wide range of temperatures (Miyata 1996). Glass fibre reinforced plastics has been used for soil nailing in Germany and composite ground anchors have been used in Paris, for supporting the basement of multistory buildings (Burgoyne 1999). Geo-grids based on FRPs are suitable for providing high strength and stiffness and low creep. However, besides mechanical properties, the surface characteristics of FRPs is also an important factor, which has strong influence on the interface between soil and FRPs and therefore, on the performance of the reinforced soils.

In the present paper, innovative FRP rods have been developed for application in soil reinforcement systems. These FRP rods have been produced using the braiding technology, which is a simple and low-cost textile manufacturing process. Additionally, braided structures offer several benefits when compared to other techniques, such as excellent impact and damage tolerance, conformability, allows in-plane multi-axial orientations and core reinforcement, etc (Swanek 2009). Besides that, the FRP rods produced through the braiding technology possess a ribbed surface texture, which may provide better interfacial interactions with soils, as seen with other types of matrices such as cement (Fangueiro 2006). Braided FRP rods have been developed using different types of core fibres and their mixture and also using both thermosetting and thermoplastic matrices, in order to get a wide range of mechanical properties. In addition to that, attempt has been made to introduce piezoresistivity and strain sensing property to the braided rods using carbon fibre in the core, targeting to develop a reinforcement material capable of performing online health monitoring of geotechnical structures. The influence of carbon fibre % on the piezoresistive behavior has been studied, in order to investigate the optimum core composition for achieving excellent strain sensing property.

The experimental work reported in this paper is mainly concerned with the development of smart and innovative materials for geotechnical applications. Future work will be directed towards implementing these developed materials for soil reinforcement and investigating the behavior of reinforced earth structures using their sensing properties.

2. Raw materials

The fibres used for core fibres were E-glass (G), carbon (C), HT polyethylene (HT PE) and sisal (S) fibres. Polyester multi-filament yarns were used in the braided cover. For thermosetting matrix, unsaturated polyester resin was used, whereas polypropylene (PP) fibres were used to form the thermoplastic matrix.

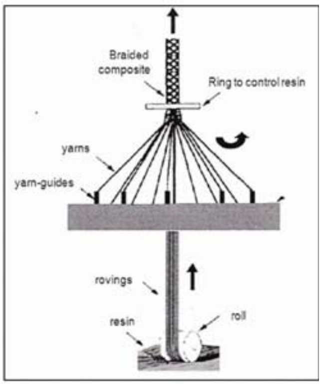
Sisal fibres were treated with alkali to improve the interface between sisal fibres and PP matrix.

For this purpose, a bundle of sisal fibres was soaked with a solution containing 0.15 wt.% of NaOH and 0.2 wt.% of a wetting agent (Erkantol), for 20 minutes at 98°C. This was followed by washing of the fibres with water and neutralizing alkali with 0.025 wt.% of sulfuric acid, till the drained water achieves a pH value between 6 and 8. Finally the fibres were dried in an oven at 70°C.

3. Production of BCR

Braided rods were produced in a vertical braiding machine using polyester yarns for the braided cover and different types of core fibres, as mentioned in the raw materials section. The braiding process is illustrated in Fig. 1(a), which shows that a braided fabric is being produced around the core fibres. For the production of BCRs with thermosetting matrix, an additional resin bath was introduced for impregnation of core fibres before going to the braiding machine (Fangueiro 2004). The process has been shown in Fig. 1(b). It was observed that a braiding angle of 23-24° was necessary for the optimum performance of BCRs. The composite rods were then cured at environmental temperature and moisture conditions (20 ± 2°C and 50 ± 5%). Produced BCRs and their surface texture are shown in Fig. 2.

(a)



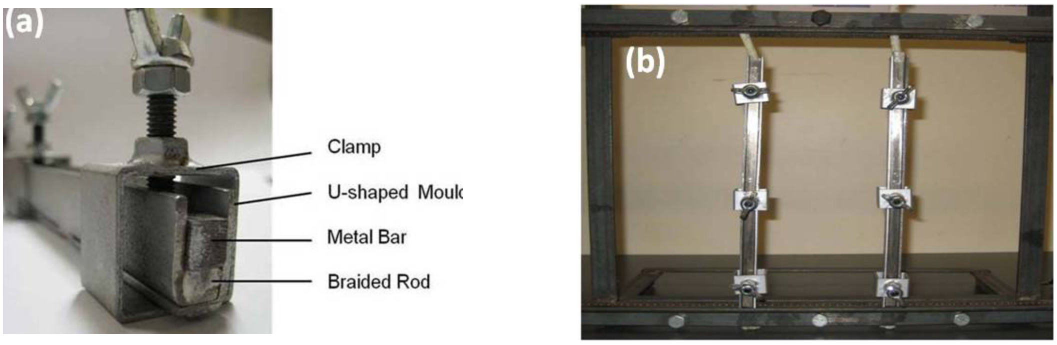
(b)

Fig. 1 Vertical braiding process (a) and production of BCR (b)

(a)

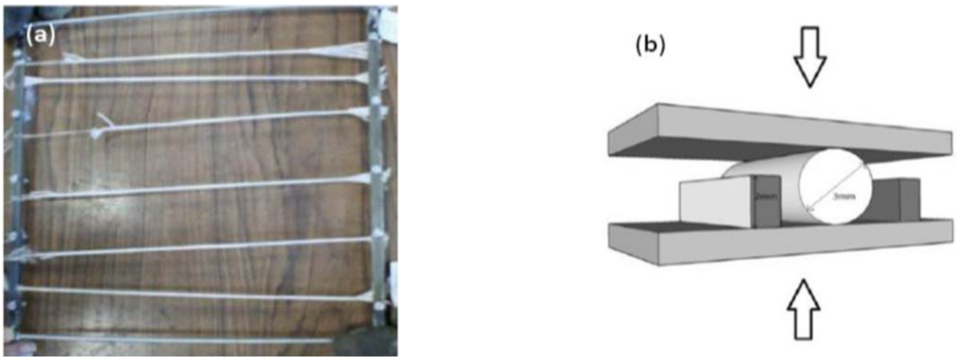
(b)

Fig. 2 BCRs (a) and their surface texture (b)



(a) (b)

Fig. 3 Setup for (a) consolidation; and (b) aligning core fibres for glass/PP BCR



(a) (b)

Fig. 4 Setup for aligning (a) core fibres; and (b) consolidation for sisal/PP BCR

In case of thermoplastic matrix, PP fibres were blended with the core fibres, before feeding to the braiding machine. Braided composites were formed when the produced structures were consolidated under heat and pressure using special moulds. The mould used for the glass/PP BCR is shown in Fig. 3. The mould was U-shaped and pressure was exerted to the braided composites using a metal bar with the help of 3 clamping devices, fitted along the length of the mould. The mould was fixed to a frame, which was used for aligning the core fibres and was placed in an oven for 30 minutes at 190°C for consolidation.

In case of sisal/PP BCR, the used frame for core alignment and mould for consolidation are shown in Fig. 4. The consolidation was performed, in this case, in a compression molding machine at 160°C for 20 sec., using 5 ton pressure.

4. Characterization

4.1 Characterization of tensile properties

Braided composites were characterized for tensile properties in a Universal Testing Machine (Hounsfiled H100 KS) using conditions and test parameters according to ASTM D3916-94.

4.2 Characterization of piezoresistivity

The strain sensing behavior of the BCRs was characterized by measuring the change in electrical resistance between the sample ends using two terminal dc method under cyclic 3-point flexural loading. Cyclic tests were performed at low strain range (up to 0.55%) in order to investigate the performance of the BCRs in sensing very low deformation in continuous manner. The experimental setup for the characterization of piezoresistive behavior is shown in Fig. 5 and the testing parameters are provided in Table 1.

The electrical resistance of the samples was continuously measured during the flexural test by making electrical connections between the two probes of a digital multi-meter (Agilent 84401A) and sample ends through gold wires fixed to the samples using silver paste. The strain sensing capability of the composites was evaluated in terms of Gauge Factor (GF), which is defined as follows

$$GF = \frac{\Delta R / R}{\in} \tag{1}$$

where, ΔR is the change in electrical resistance, R is the initial resistance, $\Delta R/R$ is the fractional change in resistance and $\in$ is the flexural strain at the outer surface of specimen at midspan, which was calculated from maximum deflection of the center of the rod (D), diameter (d) and support span (L) using the following formulae

$$\in = \frac{6Dd}{L^2} \tag{2}$$

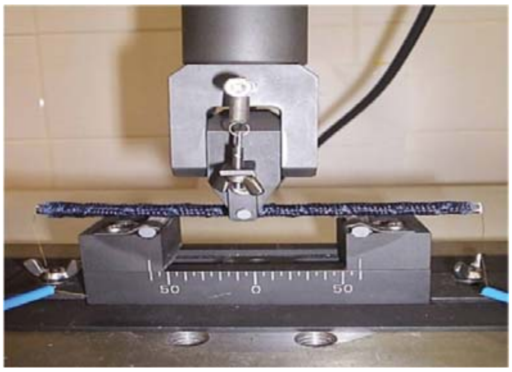


Fig. 5 Setup for characterizing piezoresistive behavior of BCR

Table 1 Testing parameters for characterization of piezoresistive behavior

Parameters	Values
No. of cycles	4
Span length (mm)	60
Sample length (mm)	138
Displacement limit (mm)	0.55
Crosshead speed (mm/min)	0.3

5. Results and discussion

5.1 Tensile properties

The tensile properties of BCR with thermosetting matrix are listed in Table 2 (Gonilho-Pereira 2010). It can be observed that these BCRs have different mechanical properties depending on their composition. BCR with 100% carbon fibre core presented the highest elastic modulus among all BCRs. Moreover, use of carbon fibres also led to higher tensile strength than 100% glass core composites. However, a combination of higher amount of glass with carbon fibres (77/23) resulted in better tensile strength than 100% carbon rods. This is probably attributed to the capability of higher amount of glass fibres to sustain the load even after the breakage of carbon fibres. This phenomenon is commonly known as pseudo-ductility and results in better tensile strength and elongation. Therefore, using a lower amount of carbon fibres in combination with higher amount of glass fibres is beneficial to improve tensile strength and elongation, however, at the cost of elastic modulus. It can also be noticed that incorporation of HT polyethylene fibres resulted in improved tensile strength of BCR.

Table 2 Tensile strength and elastic moduli of thermosetting BCR (polyester matrix) with various core compositions

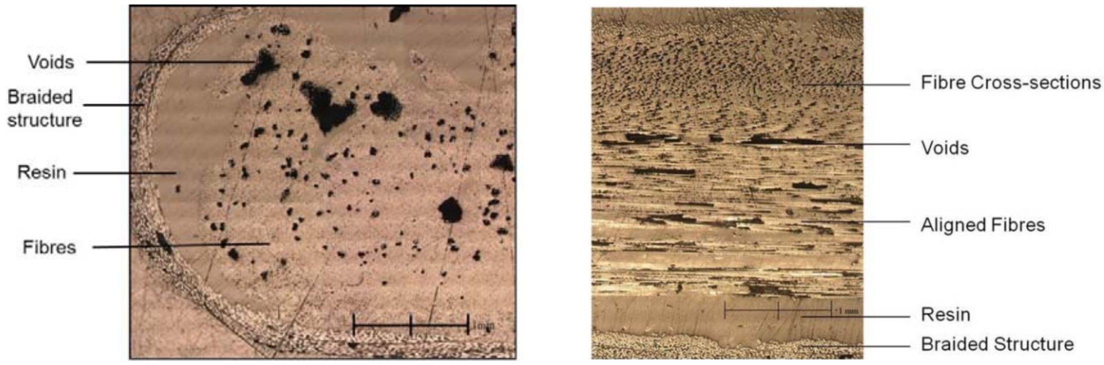
Core Composition	Type of matrix	Fibre mass (%)	Tensile strength (MPa)	Elastic modulus (GPa)
100% G	Polyester	41	485	55
77% G, 23% C	Polyester	35	767	78
53% G, 47% C	Polyester	32	740	74
100% C	Polyester	33	748	96
50% G, 45% C, 5% HT PE	Polyester	35	679	84
52% G, 45% C, 3% HT PE	Polyester	33	653	81
75%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

Table 3 Tensile strength and elastic moduli of thermoplastic BCR (PP matrix) with various core compositions

Core Composition	Type of matrix	Fibre mass (%)	Tensile strength (MPa)	Elastic modulus (GPa)
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
100% S	PP	25	37	1.8
100% S	PP	33	48	3.2
100% AT-S	PP	33	64	3.3

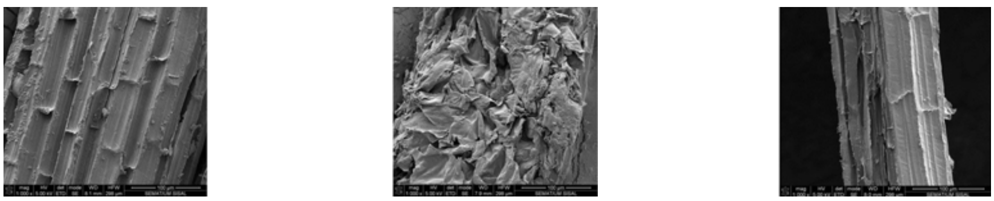
*Glass/polypropylene composite produced from commercial Twintex® roving

Tensile properties of BCR with thermoplastic matrix are listed in Table 3. It is clear that both tensile strength and elastic modulus of glass/PP BCRs improved significantly with the increase in glass fibre%. This is due to the fact that the axial glass fibres are the main load bearing component in these composites. It can be noticed that the mechanical properties of these new braided rods are lower than the glass/PP composites, fabricated through consolidation of commercial Twintex® rovings, in which glass and polypropylene fibres are distributed homogeneously within the cross-section using commingling process. Besides that, inhomogeneous fibre distribution and presence of voids are also responsible for reduction in mechanical properties. Fig. 6 shows the cross-sectional and longitudinal views of braided composite rods having 80 wt% glass fibre as seen under the optical microscope. It can be seen from the cross-sectional view that the glass fibres are located more in the centre of the rods and, matrix rich regions can be clearly seen near the boundary. Moreover, the composite rods contain significant amount of voids which can be observed as dark spots in the figure. The presence of voids can also be observed from the longitudinal view. Moreover, the longitudinal view shows the presence of aligned glass fibres and

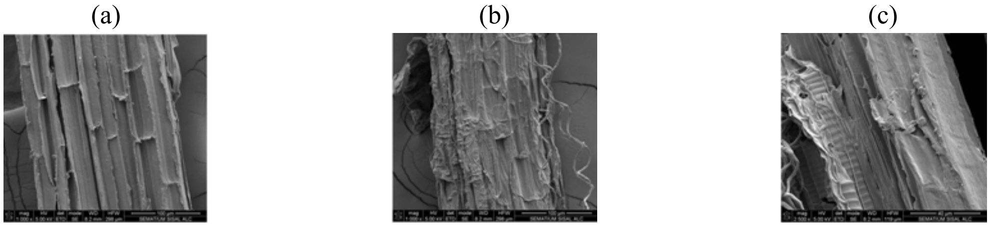


(a) (b)

Fig. 6 (a) Cross-sectional; and (b) longitudinal view of braided composites as observed by optical microscope



(a) (b) (c)



(a1) (b1) (c1)

Fig. 7 Surface morphology of sisal fibres before (a, b, c) and after (a1, b1, c1) alkali treatment as observed by SEM also some fibre cross-sections, implying that some of the glass fibres were not aligned. Therefore, mechanical properties of glass/PP braided composites can be further enhanced by ensuring proper alignment of glass fibres as well as their homogeneous distribution within the matrix.

It is also evident from Table 3 that an increase in sisal fibre % in the core (from 25% to 33%) improved tensile strength by nearly 30% and elastic modulus by 77%. Moreover, the BCR with alkali treated sisal fibres (AT-S) showed considerably higher strength (33%) as compared to untreated fibres. This is due to the higher strength of alkali treated sisal fibres, as well as, due to stronger interface formed with the PP matrix in case of alkali treated fibres. The improvement of sisal fibre strength and interface with the PP matrix was due to the removal of weak components such as hemicellulose and lignin from the fibre structure after alkali treatment. The removal of these components can be clearly seen from the much cleaner surface of sisal fibres after alkali treatment, as can be seen from Fig. 7.

5.2 Strain sensing behavior

Fig. 8 shows the type of response observed with BCR having 23% carbon core. It can be seen that the resistance change with deformation is quite reversible, except a slight decrease in resistance in each cycle. This small reduction in resistance was probably attributed to the permanent changes in the electrical contact points in each cycle. This fact was also observed in further cycles at this strain level (~ 0.5%) and but was absent for lower values of strain (0.1% or lower), where the strain sensing behaviour was completely reversible. The other braided composites also showed similar responses. However, the extent of resistance change with deformation was different for different BCRs. The fractional change in resistance in different cycles and the average gauge factors for different BCRs are listed in Table 4.

As reported previously (Bakis 2001), the zero-frequency resistance change of carbon fibre composites may be due to (a) dimensional change as a result of elastic deformation of fibres, (b) change of resistivity resulting from change in inter fibre contacts due to strain or change in fibre arrangements and (d) fibre breakage. Since, the composites were subjected to a low strain level in the present study and the piezoresistive behavior was quite reversible, the effect of dimensional change and fibre breakage was expected to be negligible.

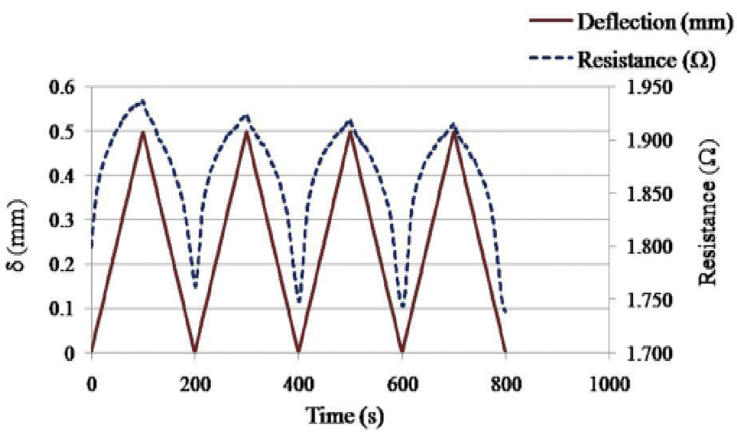


Fig. 8 Piezoresistive behavior of BCR

Table 4 Fractional resistance change and average gauge factor of BCRs

Cycles / BCR type	1		2		3		4		Average GF
	Micro-Strain	Δ*R*/*R*	Micro-strain	Δ*R*/*R*	Micro-strain	Δ*R*/*R*	Micro-strain	Δ*R*/*R*	
23% C	4800	0.10	4800	0.11	4800	0.12	4800	0.12	23.4
47% C	4800	0.04	4800	0.02	4800	0.01	4800	0.01	4.2
100% C	5500	0.02	5500	0.01	5500	0.01	5500	0.01	2.3

The role of inter fiber contacts was believed to be the dominating factor for resistance change in the studied braided composites. The change of electrical contact points is expected to be more with misaligned fibre arrangements due to the possibility of fibre alignment upon deformation (Wang 1996). The misaligned arrangement of conductive carbon fibres, therefore, resulted in very good strain sensitivity of the studied BCRs.

It can be noticed that the highest piezoresistive behavior is obtained with 23% C and the strain sensibility decreases with increase in the carbon fibre %. In the composites with higher amount of carbon fibres, there will be less change in electrical contacts during deformation due to more touching of fibres leading to a large number of electrical contact points throughout the composites. Previous researchers also found less strain sensitivity with higher % of carbon fibres in tensile loading due to decrease in the "electrical ineffective length" (Park 2001) (average length between adjacent two contact points of misaligned carbon fibres) with the increase in carbon fibre % (Okuhara 2006). The trend of fractional resistance change with strain in the first cycle has been presented in Fig. 9. It is interesting to note that the curve for 23% carbon core presents more non-linearity than the other BCRs. The fractional resistance change sharply and linearly up to 0.1% strain and then more gradually at higher strains due to saturation in the electrical contacts. This behavior was also observed in continuous carbon fibre composites where resistance change was mainly attributed to the change in electrical contact points (Park 2001).

Further research is going on to characterize the sensing behavior of BCR under higher strain

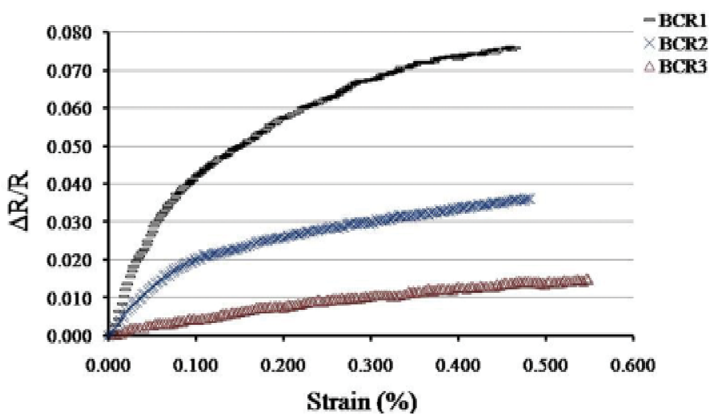


Fig. 9 Fractional change in resistance with strain% of BCR1 (23% carbon), BCR2 (47% carbon) and BCR3 (100% carbon)

level both in cyclic and monotonic tests. According to the preliminary results (Rosado 2010), at higher deformation, the electrical resistance changes in irreversible manner, due to permanent changes in the structure and the resistance does not come to the initial point, and increases, to some extent, in each cycle. However, after a certain high strain level, the resistance increases sharply due to the breakage of carbon fibres and discontinuity in the conductive network. Efforts are also being made to optimize the composition of BCR, in order to detect damage in the structure well before the complete rupture of carbon fibres.

From the above results, it is clear that the developed fibrous materials possess suitable mechanical properties and monitoring capability for application in smart geotechnical structures. However, there are a few important factors which are to be considered for their long-term performance when implemented for these applications. Firstly, the developed materials should have sufficient resistance to chemical degradation when used for soil reinforcement. The developed BCRs are expected to possess good resistance to chemical degradation, as their structure is protected by the chemically resistant polyester fibre cover, as well as, by thermoplastic and thermosetting matrices. The thermoplastic PP matrix is highly stable towards chemical degradation, whereas, a thermosetting matrix such as epoxy can be chosen to provide excellent resistance to chemicals. Although natural plant fibres like sisal have low chemical resistance, the developed BCRs using them are expected to be resistant to chemicals, due to the protective layers of braided cover and PP matrix. Secondly, the developed materials should show low level of creep or time dependent deformation under loading conditions. FRPs made of thermosetting matrices are usually low creep materials. However, thermoplastic matrices like PP have the demerits of higher creep, which tends to be even more with the increase in temperature or stress level. Recent research findings have demonstrated that the creep of thermoplastic polymers can be reduced considerably through incorporation of various nanoparticles such as nano TiO_2, SiO_2, etc. (Zhou 2007) and therefore, PP fibres can be modified using these nanoparticles, before using in BCR matrix, to improve the creep behavior.

6. Conclusions

In the present study, an innovative fibrous material, known as, braided composite rods (BCRs) have been developed for soil reinforcement applications. It was possible to develop these rods using both thermo-setting and thermoplastic matrices. Natural fibre based thermoplastic BCRs were also produced as low cost, light weight, sustainable and recyclable reinforcement systems for soils. BCRs showed tailorable and wide range of mechanical properties, depending on the type of fibres used in the core. It was also possible to introduce piezoresistivity in these materials using carbon fibre core and, a combination of lower quantity of carbon fibre (23%) with glass fibres (77%) exhibited the best strain sensing behavior (gauge factor 23.4) under very low flexural deformation (0.5%). Moreover, BCRs presented a characteristic ribbed surface texture which may provide excellent interface with soils and improve their mechanical performance. Therefore, the innovative materials developed in this research can be advantageously applied for reinforcing soils as well as for continuous health monitoring of geotechnical structures. Future attempts will be directed towards improving the manufacturing process of thermoplastic BCR, in order to ensure homogeneous fibre distribution and fibre alignment and to produce defect free braided composites. Creep phenomena and resistance of BCR towards chemical and other degrading conditions will be assessed to study their long-term performance. Also, different type of soils will be reinforced using these innovative materials and the performance of the reinforced soils will be evaluated.

References

Bakis, C.E., Nanni, A., Terosky, J.A. and Koehler, S.W. (2001), "Self-monitoring, pseudoductile, hybrid FRP reinforcement rods for concrete applications", *Compos. Sci. Technol.*, **61**(6), 815-823.

Binici, H., Aksogan, O. and Shah, T. (2005), "Investigation of fiber reinforced mud brick as a building material", *Construct. Build. Mater.*, **19**(4), 313-318.

Burgoyne, C.J. (1999), "Advanced composites in civil engineering in Europe", *Struct. Eng. Int.*, **9**(4), 1-7.

Fangueiro, R., Sousa, G., Araujo, M., Pereira, C.G. and Jalali, S. (2006), "Core-reinforced composite armour as a substitute for steel in concrete reinforcement," International Symposium Polymers in Concrete, ISPIC2006, Guimaraes, Portugal.

Fangueiro, R., Soutinho, F., Jalali, S. and Araujo, M. (2004), "Development of braided fabrics for concrete reinforcements", The 4th World Textile Conference Autex, Czech Republic.

Gonilho-Pereira, C., Jalali, S., Fangueiro, R., Araújo, M. and Marques, P. (2010), "Hybrid composite rods for concrete reinforcement", *ICSA 2010 - 1st International Conference on Structures & Architecture*, Guimaraes, Portugal, July.

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.

Miyata, K. (1996), "Walls reinforced with fiber reinforced plastic geogrids in Japan", *Geosynth. Int.*, **3**(1), 1-11.

Okuhara, Y. and Matsubara, H. (2006), "Memorizing maximum strain in carbon-fiber-reinforced plastic composites by measuring electrical resistance under pre-tensile load", *Compos. Sci. Technol.*, **65**(14), 2148-2155.

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.

Park, J.B., Okabe, T., Song, D.Y., Takeda, N. and Kitano, A. (2001), "In-situ health monitoring of CFRP composites using electrical characteristics", *Proceedings of SPIE Smart Structures and Materials*, **4328**, 323-331.

Prabakar, J., Dendorkar, N. and Morchhale, K. (2004), "Influence of fly ash on strength behavior of typical soils", *Construct. Build. Mater.*, **18**(4), 263-267.

Rosado, K. (2010), "Intelligent fibre reinforced composite rods for concrete reinforcement", *Master Thesis*, University of Minho, Portugal.

Swanek, D.S.S. and Carey, J. (2009), "Braided composite materials for the production of lightweight, high rigidity golf shafts", *Sport. Eng.*, **10**(4), 195-208.

Wang, X. and Chung, D.D.L. (1996), "Continuous carbon fibre epoxy-matrix composite as a sensor of its own strain", *Smart. Mater. Struct.*, **5**(6), 796-800.

Yarbasi, N., Kalkan, E. and Akbulut, S. (2007), "Modification of freezing–thawing properties of granular soils with waste additives", *Col. Reg. Sci. Technol.*, **48**(1), 44-54.

Zhou, T.H., Ruan, W.H., Yang, J.L., Rong, M.Z., Zhang, M.Q. and Zhang, Z. (2007), "A novel route for improving creep resistance of polymers using nanoparticles", *Compos. Sci. Technol.*, **67**(11-12), 2297-2302.

GM