MECHANICAL PROPERTIES OF BRAIDED REINFORCED COMPOSITES

R. Fangueiro[1], C. Gonilho Pereira[1], S. Jalali[2], M. de Araújo[1]
University of Minho
Department of Textile Engineering[1]
Department of Civil Engineering[2]
Campus de Azurém, 4800-053 Guimarães, Portugal
rfang@det.uminho.pt

Abstract
This work presents the study that is being done at University of Minho concerning the development of braided reinforced composites for civil engineering purposes. A research study has been undertaken to understand the mechanical behaviour of core reinforced braided fabrics. Various samples have been produced using polyester fibers, for the production of the braided fabric, and glass, carbon, polyethylene and sisal fibers, for the core reinforcement. The results of tensile and bending tests carried out in the correspondent core reinforced braided fabrics obtained are presented and discussed. Moreover, the influence of the testing conditions and the braiding angle is also presented and discussed. In order to produce braided reinforced composite rods to be used as concrete reinforcement, a special technique has been developed using a standard vertical braiding machine. The tensile and bending properties of braided reinforced composite rods have been evaluated and the results obtained are presented, discussed and compared with those of conventional materials, such as steel.

Keywords: concrete, fiber reinforced composite materials, core reinforced braided fabric, core reinforced braided composite

1. Introduction

Fiber reinforced composite materials have recently received a great deal of interest in the civil engineering research community [1]. This interest is a result of the overwhelming demand placed upon a decaying infrastructure caused by the corrosion of steel reinforcements [2]. Many techniques have been developed in recent past to reduce corrosion of steel, such as galvanizing, epoxy coating, and others, but none of the solutions seem to be viable as suitable solution to the corrosion problem [3]. The advantages of fiber reinforced composite materials over steel include the excellent corrosive resistance, mechanical properties similar to steel, high strength-to-weight (10 times higher than steel), excellent fatigue resistance, non-magnetic properties and low thermal expansion [2, 3]. Many engineers consider fiber reinforced composite materials as one of the most innovative materials that may overcome the inherited deficiency of reinforcing concrete structures by steel rebars in harsh environments due to corrosion [4]. Therefore these materials are emerging worldwide as one of the most promising technologies of this decade.

In fiber reinforced composite materials, fibers are used as reinforcement, possessing high tensile strength and stiffness, while the matrix, usually a polymeric material, is used to hold fibers together, to transmit the shear forces and also to act as a coating. The selection of suitable fibers is determined by the required values of stiffness and tensile strength of a composite. Further criteria for the choice of suitable reinforcing fibers include elongation at failure, thermal stability, adhesion among fibers and matrix, dynamic and long-term behaviour, price and processing costs.

Driven by the need for economical manufacturing of damage tolerant composites for structural applications, textile performing has increasingly been recognized as an important component in the composite manufacturing system [5].

To produce fiber reinforced composite rods, several manufacturing textile techniques may be used. Pultrusion and braiding techniques are the most common due to low cost, high quality and efficient fiber orientation [2, 6]. Braiding technique is probably the most ancient production process of textile structures. Normally used for ropes and cables, braided fabrics are also very interesting for composite reinforcements due to their characteristics, such as in-plane multiaxial orientation, conformability, excellent damage tolerance and low cost [5, 7]. Braiding technique allows the reinforcement of the braided fabric core. A wide range of mechanical properties, such as ultimate stress, rupture strain and modulus of elasticity are achieved when the core is reinforced by different types of fiber. According to the results obtained in previous research works [8, 9], the mechanical behaviour of the core reinforced braided fabrics is mainly dependent on the core reinforcement performance, while the contribution of the braided fabric itself is rather poor. These properties are also affected by the fiber volume fraction of the core braided fabric when composites are produced [2]. In the braiding technique, the number of yarn bobbins used limits the dimensions of the fabric produced [7].

2. Experimental work.

2.1 Experimental plan

The understanding of mechanical properties, of core reinforced braided fabrics composites, is of paramount importance. Tensile and bending tests have been carried out in braided fabrics and in composite rods.

Braided fabrics have been produced on a vertical braiding machine (Figure 1). A study on the influence of the braiding angle on the mechanical performance of core reinforced braided fabrics has been undertaken. Various braided fabrics, core reinforced with glass fiber, were produced, varying the braiding machine speed production and, therefore changing the braided fabric angle.

Figure 1 – Lab braiding machine

A study on the influence of the core reinforcement fiber type in the mechanical properties of the core reinforced braided fabrics has also been undertaken. Glass, carbon, polyethylene and sisal fibers have been used as axial reinforcement and tensile tests have been performed (Table 1). In order to increase roughness of the composites produced with the core reinforced braided fabrics, the braided structure has been produced as a rib structure.

Table 1 – Braided fabric and core reinforcement fibers: type, count and number of rovings/fibers.

	Braided Fabric	**Core Reinforcement**			
Type of fiber	Polyester	Glass	Carbon	Polyethylene	Sisal
Yarn count [Tex]	110	900	1600	176	37,8
Number of rovings/fibers used	6 bobbins with 1 yarn	2	1	10	45
	2 bobbins with 4 yarns each				
Total yarn count [Tex]	1540	1800	1600	1760	1701

It has been also studied the influence of pre-load on the mechanical behaviour of the core reinforced braided fabrics (25N, 50N and 100N pre-load).

Braided reinforced composite rods have been produced impregnating the core reinforced braided fabrics with a vinylester resin. The production of the core reinforced braided fabrics and its impregnation was performed in a single step [9, 10]. Tensile and bending tests were carried out on braided reinforced composite rods.

2.2. Braided fabrics optimal angle

In order to identify the braided fabric angle that guarantees optimal mechanical behaviour, several samples have been prepared. Eight polyester bobbins were used to produce the braided structure and 2 rovings of glass fiber were used as core reinforcement, as presented in Table 1. The braided fabric angle varies according to the braiding speed production. Braiding angles have been identified for each braided fabric produced. Tensile tests were carried out according to test method described by others authors [7 to 10]. Table 2 presents results obtained.

Table 2 – Relationship between speed production, braided fabric angle and tensile ultimate strength and elongation at failure (mean values).

Speed production [m/s]	**Angle (º)**	**Ultimate load [N]**	**Strain at failure [%]**
0,0079	26,0	829,5	2,71
0,0092	25,5	844,0	2,60
0,0123	25,0	888,2	2,86
0,0156	18,6	892,9	2,93
0,0343	13,1	795,5	2,89
0,0360	12,7	790,5	3,07
0,0406	9,7	780,9	2,67

According to Table 2, speed production and braiding angle are proportionally inverse. Higher speed production leads to a lower braided fabric angle and lower speed production leads to higher angle values, as it is shown in Figure 2.

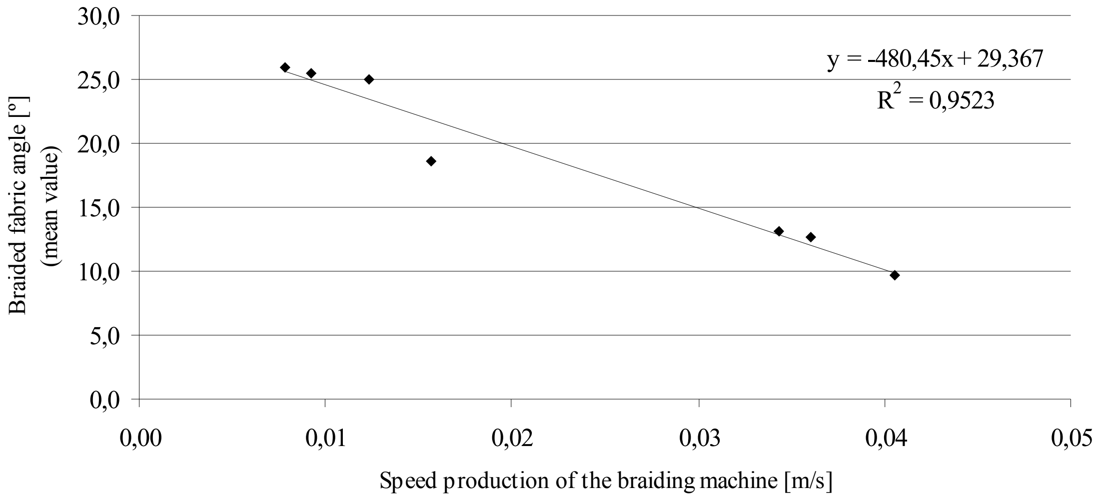

Figure 2 – Influence of speed production of braiding machine on braided fabric angle.

Analysing the influence of the braided fabric angle on the ultimate load and on strain at failure, one may conclude there is a directly proportional relationship between these factors up to a 18,6º braided angle. However, when braided fabric angle is higher than 25º, both ultimate load and strain at failure decrease with the increasing of the braided angle (Figures 3 and 4).

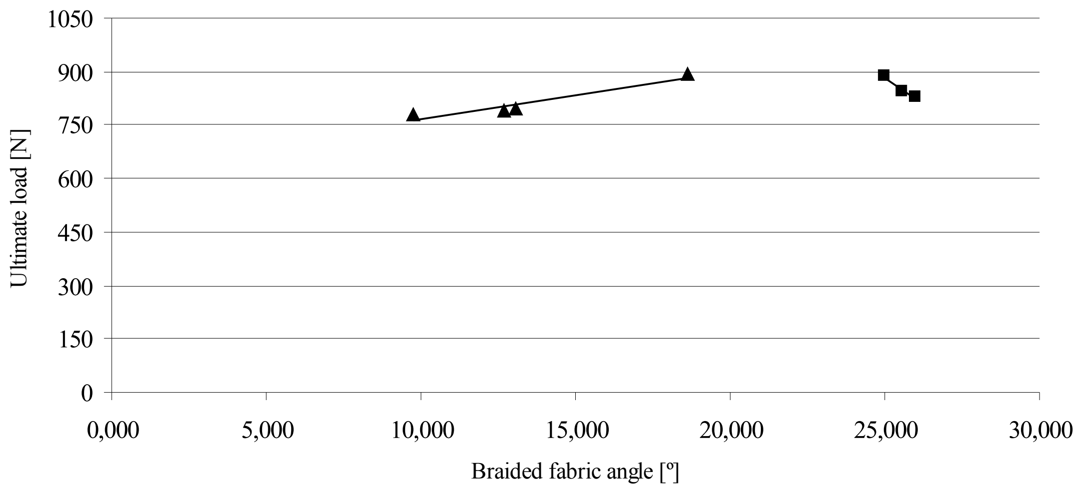

Figure 3 – Influence of braided fabric angle on tensile ultimate load (mean values).

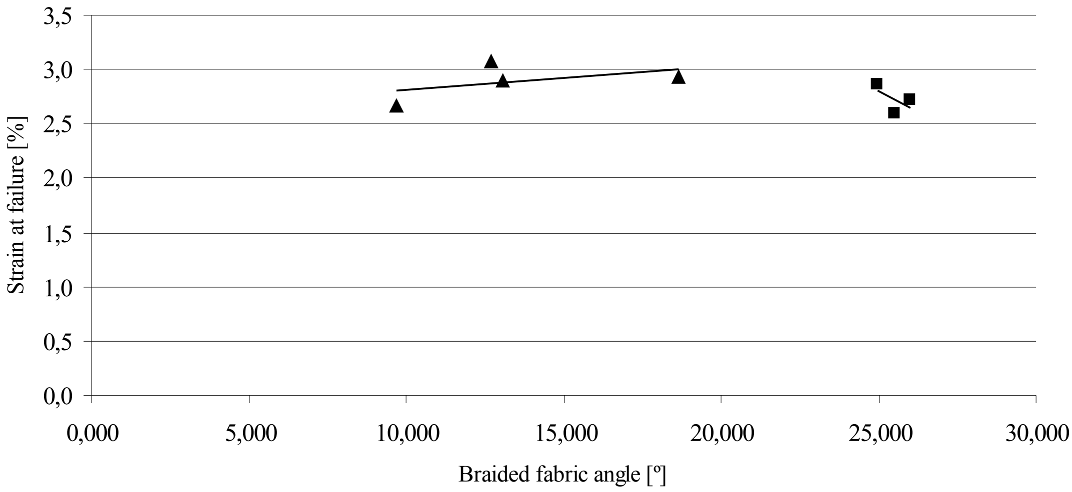

Figure 4 – Influence of braided fabric angle on tensile strain at failure (mean values).

Based on the above mentioned results, it is concluded that braided fabrics, produced with 8 bobbins of polyester, 2 of them with 4 yarns, and reinforced with 1800Tex of glass fiber, possessing angle between 18,6º and 25º, present higher tensile ultimate load and higher strain at failure.

2. 3. Core reinforced braided fabrics

Core reinforced braided fabrics were produced with different types of fibers as core reinforcement and with a speed production of 0,0156m/s. As showed in Table 1, glass, carbon, polyethylene and sisal fibers were used so that the reinforcement may present a count between 1600Tex and 1800Tex. Tensile tests were carried out on the different core reinforced braided fabrics according to the procedure explained elsewhere [6 to 9]. Tensile ultimate stress, strain at failure and initial modulus of elasticity were determined for different pre-load conditions (Table 3).

Table 3 – Tensile test results (mean values).

Pre-load [N]	**Reinforcement fiber**	**Ultimate stress [MPa]**	**Strain at failure [%]**	**Modulus of elasticity (0,2%) [GPa]**
25	Glass	662,0	2,1	19,8
	Carbon	1125,5	1,8	28,2
	Polyethylene	776,1	3,7	13,2
	Sisal	213,9	1,5	12,2
50	Glass	657,4	2,0	26,2
	Carbon	1205,5	1,7	45,2
	Polyethylene	830,2	3,1	18,7
	Sisal	195,6	1,2	12,9
100	Glass	808,3	2,2	27,0
	Carbon	1162,5	1,6	52,6
	Polyethylene	842,5	3,3	14,9
	Sisal	207,2	1,1	14,3

Braided fabrics reinforced with carbon fiber present higher ultimate stress, followed by polyethylene, glass and sisal fibers reinforcement (Figure 5). Analysing the tensile ultimate stress mean values, it can be concluded that the initial pre-load does not have significant influence on the ultimate stress. Apart from the braided fabric reinforced by glass fiber, the increase on the ultimate strength with the increase of pre-load is lower than 8,5%.

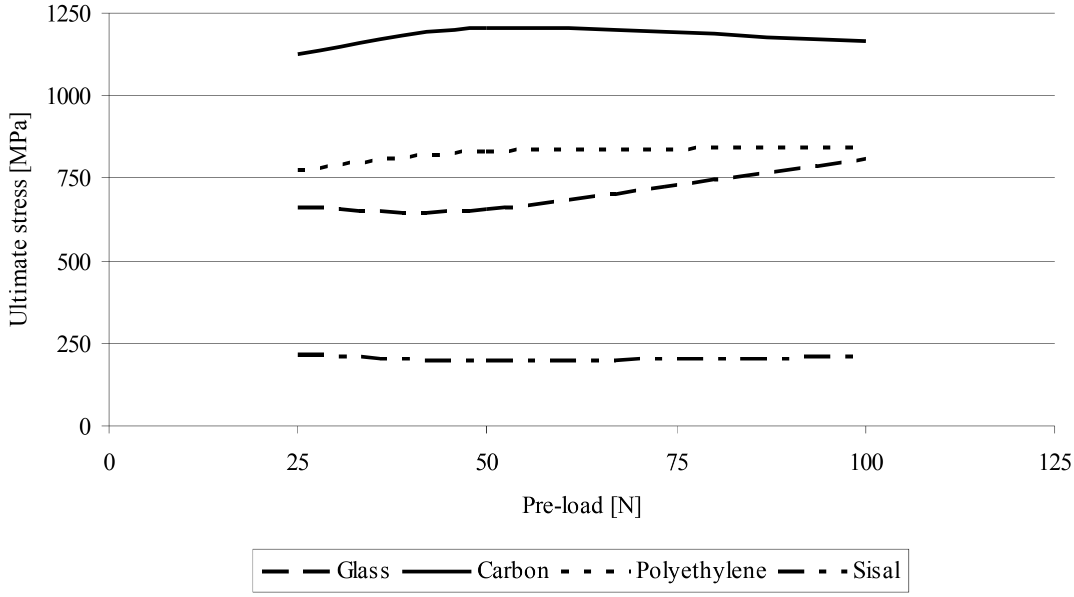

Figure 5 – Influence of initial pre-load on tensile ultimate strength (mean values).

Similar conclusion may be presented for the influence of initial pre-load on core reinforced braided fabrics tenacity (Table 4).

Table 4 – Core reinforced braided fabrics tenacity (mean values).

	Reinforcement fiber - MPa/Tex$_{(reinforcement)}$			
Pre-load [N]	Glass	Carbon	Polyethylene	Sisal
25	0,4	0,7	0,4	0,1
50	0,4	0,7	0,5	0,1
100	0,4	0,7	0,5	0,1

As expected, carbon reinforced braided fabric presents higher tenacity followed by braided fabrics reinforced by polyethylene.

Braided fabrics reinforced with polyethylene fiber presents the higher strain at failure, followed by glass, carbon and sisal fiber reinforcements (Figure 6). The influence of pre-load on strain is more significant. The increase of pre-load leads to a decrease on failure strain of 41% on sisal reinforced braided fabrics, about 11% on carbon and polyethylene reinforced braided fabrics. Braided fabric reinforced by glass fiber presents an increase of about 4% of strain when pre-load is increasing.

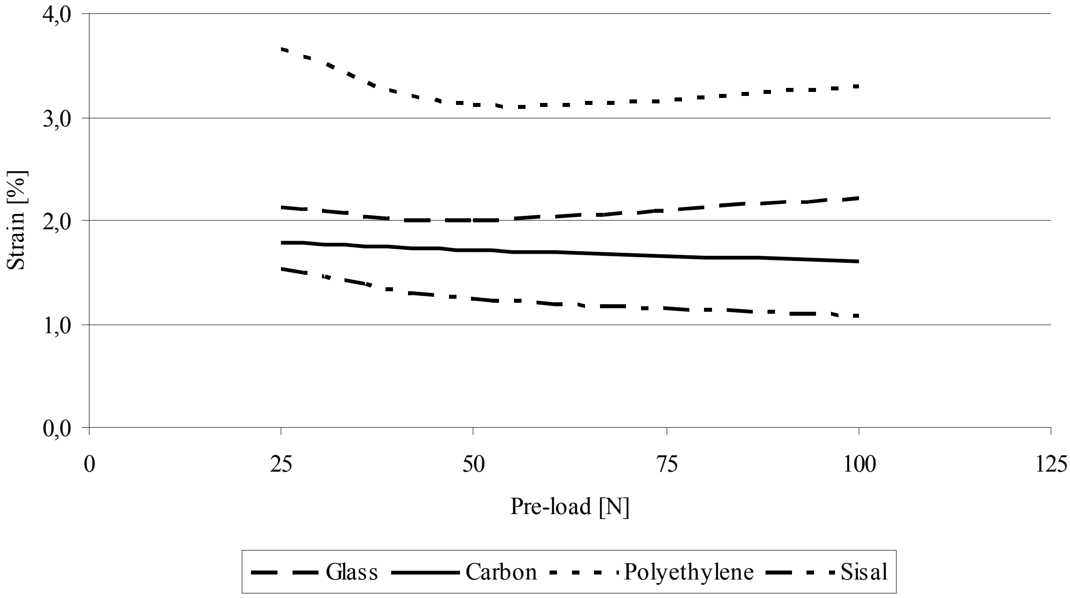

Figure 6 – Influence of initial pre-load on tensile ultimate strength (mean values).

The initial modulus of elasticity increases 7 % and 17% on sisal and polyethylene fiber reinforcement and 37% and 87% on glass and carbon fiber reinforcement when pre-load is varied from 25 to 100 N (Figure 6). Carbon reinforced braided fabrics presents the highest initial modulus of elasticity, followed by braided fabrics reinforced by glass, polyethylene and sisal fibers.

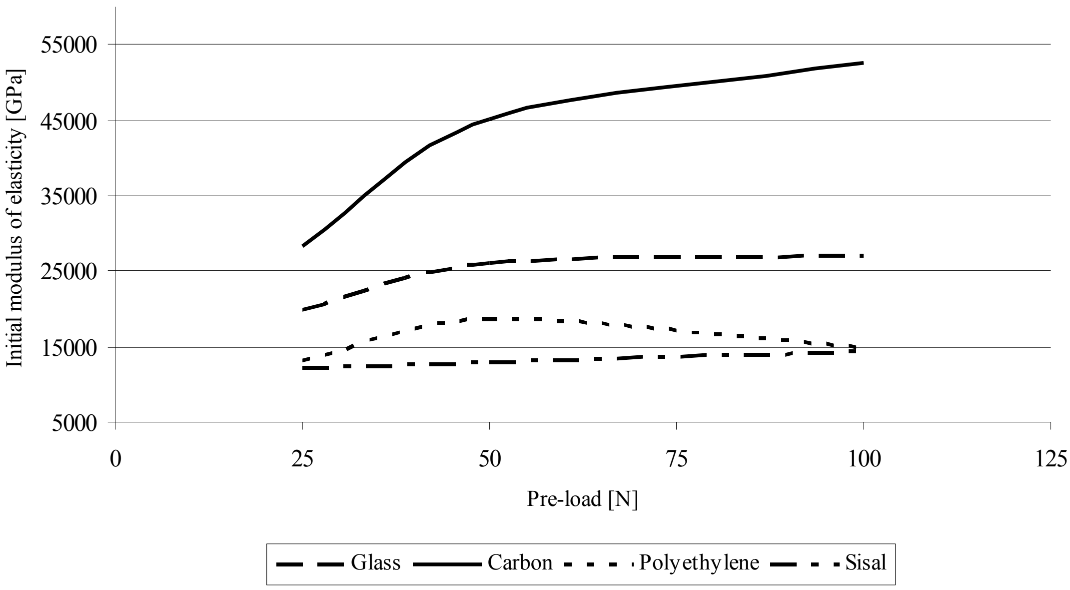

Figure 6 – Influence of initial pre-load on initial modulus of elasticity (mean values).

Initial pre-load presents a significant influence on the initial modulus of elasticity, as can be understood by the analysis of the core reinforced braided fabric tensile behaviour (Figure 7).

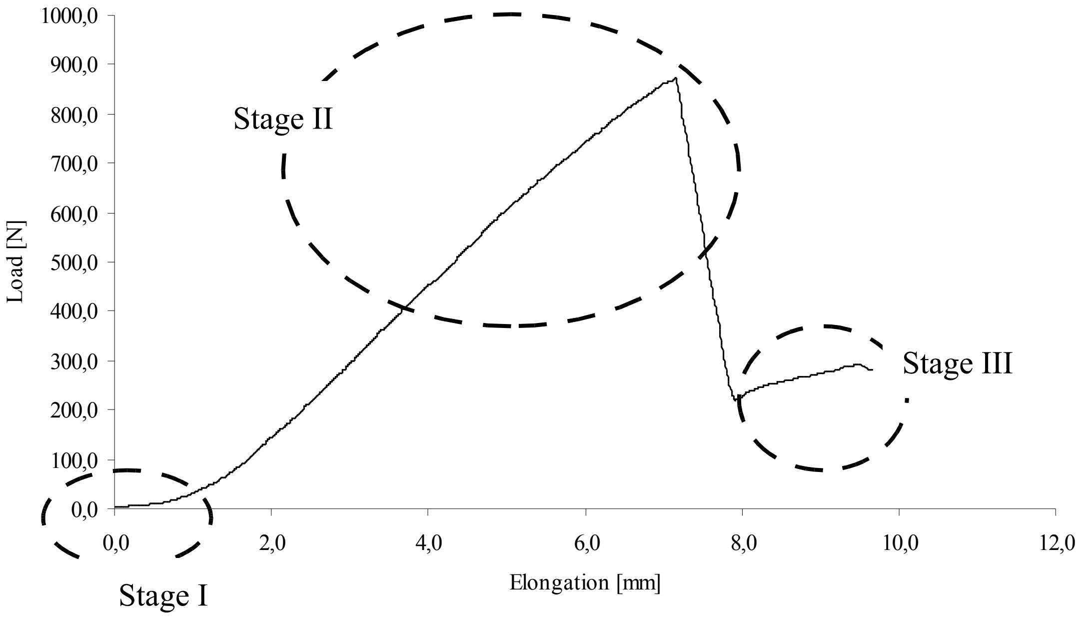

Figure 7 – Tensile behaviour of a core reinforced braided fabric.

Three stages can be identified in the load-elongation diagram for a core reinforced braided fabrics:

Stage I – load is supported by the core reinforced fibers, however fibers are still not completely straight. Braided fabric structure affects the position of the outer layer of the reinforcement rovings.

Stage II – reinforcement fibers are now completely straight and the load is still supported by the core reinforced fibers. There is a significant increase of the load supported till the reinforcement fibers breaking.

Stage III –braided fabric starts to support the load. Although braiding structures are characterized by having much higher tensile properties than compression properties (almost null) the tensile elongations are still much higher than the elongations that high performance fibers present.

Therefore, it is extremely important to assure that the core reinforced braided fabric presents all the reinforcement fibers completely straight. The influence of this factor on the ultimate stress is not significant; however the influence on initial modulus of elasticity and failure strain has to be taken in consideration.

2. 4. Core reinforced braided composite rods

Braided reinforced composite rods have been produced according to the procedure explained in previous research works [6 to 9] on a vertical braiding machine with an incorporated impregnation system. During the production of braided reinforced composite rods, braiding and resin impregnation have been done simultaneously. During the curing set time of the vinylester resin, neither the braided fabrics nor the reinforcement fibers were subjected to any value of pre-load. Bending and tensile tests were carried out on composite rods, according to the procedure explained by other authors [6 to 9]. In tensile test composite rods were subjected to a pre-load of 25N and 100N. Table 4 presents the mean value results of tensile test carried out on composite rods.

Table 4 – Tensile test results (mean values).

Pre-load [N]	**Reinforcement fiber**	**Ultimate stress [MPa]**	**Strain at failure [%]**	**Modulus of elasticity (0,2%) [GPa]**
25	Glass	537,9	4,5	9,7
	Carbon	793,5	3,3	25,0
	Polyethylene	525,3	3,9	8,7
	Sisal	121,8	2,7	4,4
100	Glass	454,5	3,5	9,0
	Carbon	685,7	2,6	23,3
	Polyethylene	473,9	3,9	7,5
	Sisal	114,6	2,3	4,3

Braided fabric composite rods reinforced with carbon fiber present higher ultimate stress, on both test conditions. Composite rods reinforced by glass fiber and polyethylene fiber present similar ultimate stress on both test conditions, with slightly higher ultimate stress when the composite rods are subjected to a pre-load of 25N. The same phenomenon occurs with composite rods reinforced with sisal fibers.

Similar conclusions can be taken in relation to failure strain and modulus of elasticity. Higher value results on 25N pre-load test condition, and composite rod reinforced by carbon fibers, presents significant higher modulus of elasticity, followed by composite rods reinforced by glass and polyethylene fibers. Composite rods reinforced with sisal fibers present the lowest modulus of elasticity. Table 5 presents the mean value results of bending test carried out on composite rods.

Table 5 – Bending test results (mean values).

Reinforcement fiber	**Bending stress [MPa]**	**Bending modulus of elasticity [GPa]**
Glass	161,0	5,9
Carbon	351,7	20,3
Polyethylene	115,8	4,1
Sisal	103,0	3,0

Braided fabric composite rods reinforced with carbon fiber present higher bending stress, followed by composite rods reinforced with glass, polyethylene and sisal fibers. Similar conclusions can be taken relatively to modulus of elasticity. Composite rod reinforced by carbon fibers, presents significant higher modulus of elasticity, followed by composite rods reinforced by glass and polyethylene fibers. Composite rods reinforced with sisal fibers present the lower modulus of elasticity.

3. Conclusions

Geometrical analysis was undertaken on braided fabrics structure. The influence of the braiding fabric angle on the mechanical performance of core reinforced braided fabrics was identified. It was concluded that for each braided fabric structure there is a braiding angle that promotes the optimized mechanical performance of the core reinforced braided structure.

Tensile behaviour of different core reinforced braided fabrics, produced with high performance fibers, has been presented and discussed. Also, results of tensile and bending tests, carried out in composite rods reinforced with core reinforced braided fabrics, are presented and discussed.

Analysing the mechanical test results obtained it is possible to identify different performances among different types of core reinforced braided fabrics and different types of braided reinforced composite rods.

Braided fabrics reinforced with carbon fibers present higher ultimate stress and modulus of elasticity and one of the lowest strains at failure values. Sisal reinforced braided fabrics present lowest ultimate stress, strain at failure and modulus of elasticity. Braided fabrics reinforced by glass and polyethylene fibers present similar mechanical properties. Analogous conclusions can be taken when analysing composite rods. Carbon reinforced composite rods present higher bending stress and higher bending modulus of elasticity. It is the composite rod reinforced by sisal fibers the one that presents lowest bending stress and lowest modulus of elasticity.

The trends in properties of core reinforced braided fabrics are similar to that of composite rods.

This work is in agreement with studies developed by other authors [6, 7], stating that the mechanical behaviour of the core reinforced braided fabrics is mainly dependent on the core reinforcement performance. It is conclude that is necessary to promote a pre-tension on the reinforcement fibers to guarantee an optimized mechanical behaviour of core reinforced braided fabrics and of the composite rods thus obtained. This work also clarifies that during the production procedure of braided reinforced composite rods it is necessary to subject the reinforcement fibers to a pre-tension condition, to get composite rods with reinforcement fibers completely straight. Otherwise, the material mechanical properties will be considerably reduced. Once the resin is cured, the reinforcement fibers of composite rods can not be straightened.

When compared with steel rebars currently used in civil construction industry, composite rods reinforced by carbon, glass and polyethylene fibers present higher ultimate stress. Current steel rebars, A235NL/R, A400NR/ER/EL and A500NR/ER/EL have ultimate stress higher than 360 MPa, 460 MPa, and 550 MPa respectively [10]. Sisal reinforced composite rods present ultimate stress much lower than steel. Although the ultimate stress of composite rods is higher than in steel rebars, composite rods have a lower modulus of elasticity when compared to 210 GPa of steel rebars.

Further research work is being undertaken in order to overcome the problems encountered and reported in this work, namely the low modulus of elasticity of composite rods. The technology used to produce the braided composite rods is being altered in order to promote a pre-tension on the reinforcement fibers, to improve the mechanical performance of braided reinforced composite rods.

References

[1] Wang, Y.C., Kodur, V. (2005), "Variation of strength and stiffness of fibre reinforced polymer reinforcing bars with temperature", Cement and Concrete Composites, 27, 864-874

[2] Soudiki, K.A. (1998), "FRP reinforcement for prestressed concrete structures", New Material in Construction, 135-142
[3] Saikia, B., Thomas, J., Ramaswamy, A. and Nanjunda Rao, K.S. (2005), "Performance of hybrid rebars as longitudinal reinforcement in normal strength concrete", Materials and Structures, 38, 857-864
[4] Alsayed, S.H., Al-Salloum, Y.A., Almusallam, T.H. (2000), "Performance of glass fiber reinforced plastic bars as a reinforcing material for concrete structures", Composites, Part B: engineering, 31, 555-567
[5] Soebroto, H.B., Pastore, C.M., Ko, F.K. (1990), "Engineering design of braided structural fiberglss composite", Structural Composites: Design and Processing Technology, 6th Annual Conference, Advanced Composites, Detroit
[6] Fangueiro, R., Soutinho, F., Jalali, S., Araújo, M. (2004), "Development of braided fabrics for concrete reinforcements", 4th World Textile Conference Autex 2004, Czech Republic.
[7] Fangueiro, R., Sousa, G., Soutinho, F., Jalali, S., Araújo, M. (2005), "Braided Fibre Reinforced Composite Rods for Concrete Reinforcement", 5th World Textile Conference Autex 2005, Portorož, Slovenia.
[8] Olcina, S.B. (2005), " Estruturas entrançadas para substituição do aço na construção civil", Projecto final de curso "Enginyeria Técnica Industrial, especialitat Têxtil", Escola Politécnica Superior d'Alcol – Universidade do Minho, Guimarães, Portugal
[9] Sousa, G. (2004), "Estruturas entrançadas para reforço do betão", Tese de Mestrado em Tecnologias de Fabricação Têxtil, Universidade do Minho, Guimarães, Portugal
[10] D'Arga e Lima, J. (1997), "Betão Armado. Armaduras: Caracterização, Fabrico, Colocação e Pormenorização. Aspectos Gerais", Laboratório Nacional de Engenharia Civil, 3.ª Edição, Lisboa, Portugal

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