THE MECHANICAL PROPERTIES OF BRAIDED REINFORCED COMPOSITES FOR APPLICATION IN CONCRETE STRUCTURES

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Abstract: *The current work is concerned with the development of braided reinforced composites for civil engineering applications. The research study aims at understanding the mechanical behaviour of core reinforced braided fabrics. Various samples have been produced using polyester fibres, for the production of the braided fabrics, and glass, carbon, polyethylene and sisal fibres, for the core reinforcement. The results of the tensile tests carried out in the various samples of reinforced braided fabrics obtained are presented and discussed. Moreover, the influence of the testing conditions and of the braiding angle are also studied. 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, fibre reinforced composite materials, core reinforced braided fabric, core reinforced braided composite*

1. INTRODUCTION

Fibre reinforced composite materials have recently received a great deal of attention by the civil engineering scientific 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 the 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 solutions to the corrosion problem [3]. The advantages of fibre reinforced composite materials over steel include the excellent corrosive resistance, mechanical properties similar to steel, high strength-to-weight ratio (10 times higher than steel), excellent fatigue resistance, non-magnetic properties and low thermal expansion [2, 3]. Many engineers consider fibre reinforced composite materials as one of the most innovative materials that may overcome the inherited deficiency of concrete structures reinforced by steel rebars, due to corrosion in harsh environments [4]. Therefore these materials are emerging worldwide as one of the most promising technologies of the decade.

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

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

To produce fibre reinforced composite rods, several manufacturing textile techniques may be used. Pultrusion and braiding techniques are the most common ones due to low cost, high quality and efficient fibre orientation [2, 6]. The braiding technique is probably the most ancient process of producing 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]. The braiding technique allows for a reinforcement of the braided fabric core. A wide range of mechanical properties, such as ultimate tensile strength, elongation at rupture and elastic modulus may be improved when the core is reinforced with the appropriate types of fibres. According to the results obtained in previous work [8, 9], the mechanical behaviour of core reinforced braided fabrics is mainly dependent on the performance of the reinforcing core, while the contribution of the braided fabric sheath is more concerned with holding the core together, protecting it and improving handling. The mechanical properties are also affected by the fibre volume fraction of the core braided fabric when composites are produced [2]. In the braiding technique, the dimensions of the fabric produced depend on the number of yarn bobbins used [7].

2. EXPERIMENTAL WORK

2.1 Experimental plan

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

The circular braided fabrics have been produced on a vertical braiding machine (Figure 1). A study of the influence of the braiding angle on the mechanical performance of core reinforced braided fabrics has been undertaken. Various circular braided fabrics, core reinforced with glass fibre, were produced, by varying the braiding machine fabric delivery speed (rate of take-up) and, therefore, changing the braiding angle of the fabric.

Figure 1 – Lab braiding machine

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

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

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

The effect of pre-tensioning (25N, 50N and 100N pre-tension) on the mechanical behaviour of core reinforced braided fabrics has also been studied.

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

2.2. Optimal braiding angle of fabrics

In order to identify the braiding angle that guarantees optimal mechanical performance, several samples have been prepared. Eight polyester bobbins were used to produce the braided structure and 2 rovings of glass fibre were used for the core reinforcement, as indicated in Table 1. In braiding, the braiding angle varies according to the braided fabric take-up rate. Braiding angles have been measured for each braided fabric produced. Tensile tests were carried out according to the test method described elsewhere [7 to 10]. Table 2 presents the results obtained.

Table 2 – Relationship between take-up rate, braiding angle, ultimate tensile strength and extension at failure (mean values).

Take-up rate [m/s]	Braiding angle(º)	Ultimate tensile strength [N]	Extension 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, fabric delivery speed (take-up rate) and braiding angle are inversely proportional. Higher take-up rates lead to a lower braiding angle and lower take-up rates lead to a higher braiding angle, as shown in Figure 2.

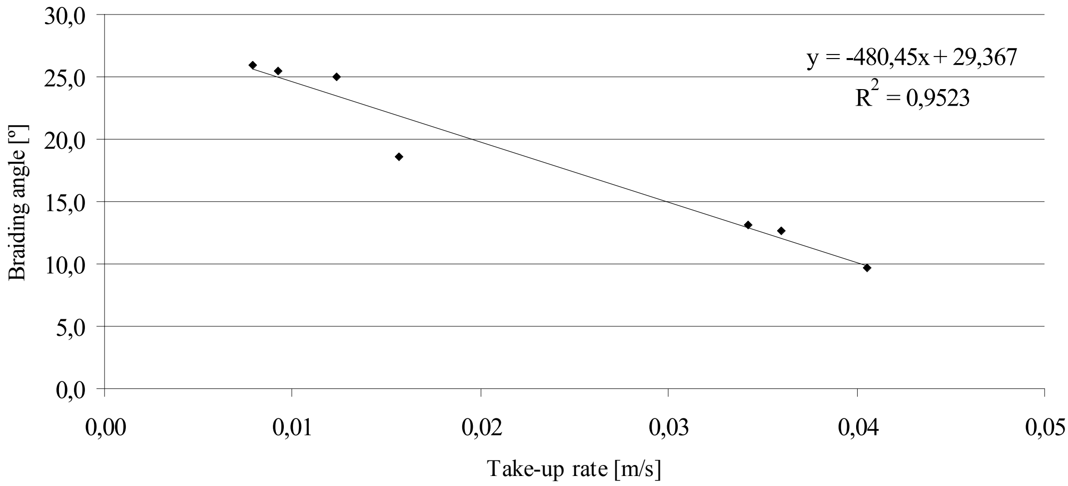

Figure 2 – Influence of take-up rate on braiding angle.

Analysing the influence of the braiding angle on the ultimate tensile strength and on the extension at failure, it may be concluded that there is an inflection on the curve. The ultimate tensile strength and the extension at failure increase as the braiding angle increases up to 18.6º. For braiding angles higher than 25º, both the ultimate tensile strength and the extension at failure decrease as the braided angle increases (Figures 3 and 4).

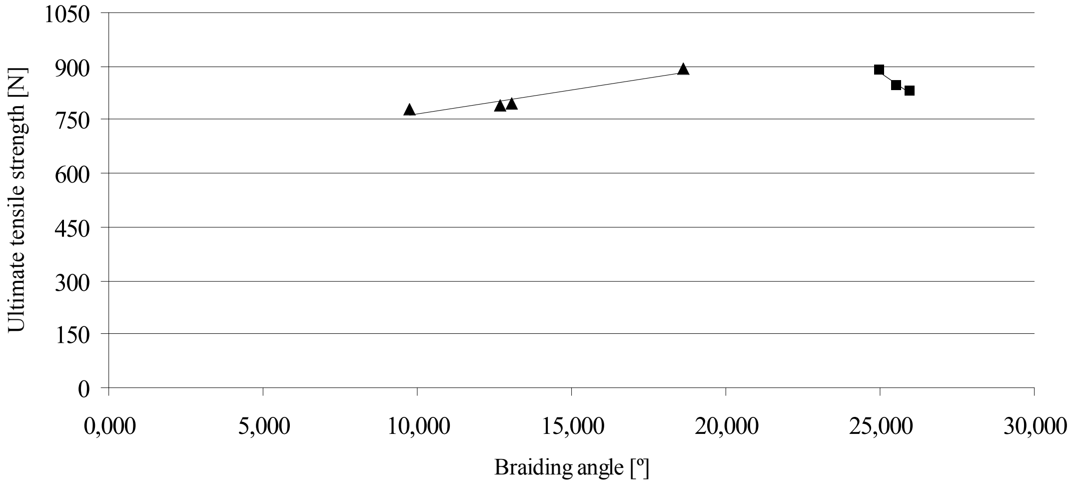

Figure 3 – Influence of braiding angle on ultimate tensile strength (mean values).

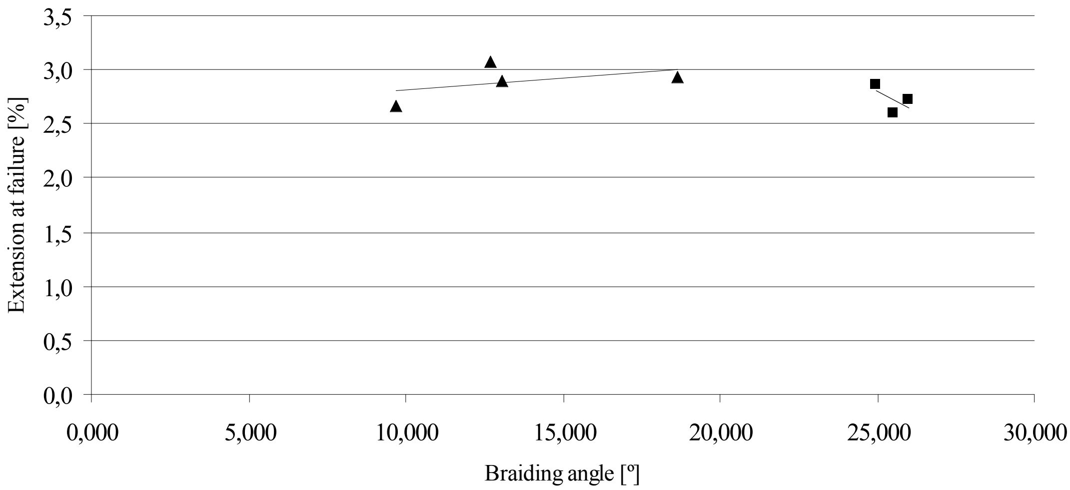

Figure 4 – Influence of braiding angle on extension at failure (mean values).

Based on the above results, it may be concluded that braided fabrics produced with 8 bobbins of polyester yarn, 2 of them with 4 yarns, and reinforced with 1800 Tex glass fibre yarns as core, achieve higher values of ultimate tensile strength and higher extensions at failure, when the braiding angles are between 18.6º and 25º.

2. 3. Core reinforced braided fabrics

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

Table 3 – Results of tensile tests (mean values).

Pre-tension [N]	Reinforcement fibre	Ultimate tensile stress [MPa]	Extension at failure [%]	Modulus of elasticity [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 fibre present the highest ultimate tensile stress, followed by polyethylene, glass and sisal fibre reinforcements (Figure 5); this does not seem to be significantly affected by the pre-tensioning conditions.

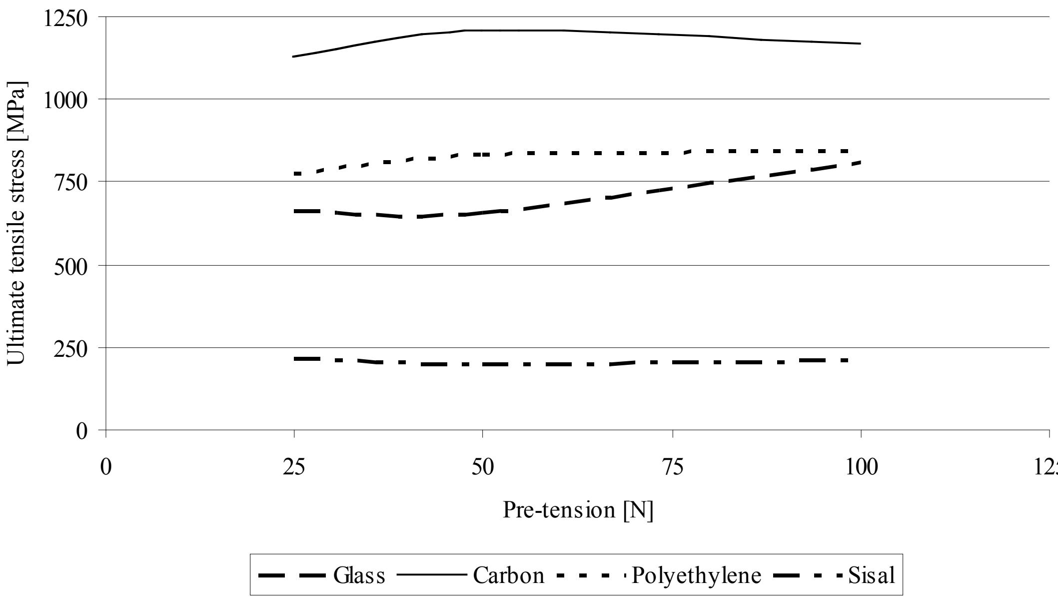

Figure 5 – Influence of initial pre-tension on the ultimate tensile stress (mean values).

A similar conclusion may be drawn for the influence of initial pre-tensioning on the core reinforced braided fabrics “tenacity” (ultimate tensile stress/ Tex of reinforcement) (Table 4).

Table 4 – “Tenacity” of core reinforced braided fabrics (mean values).

	Reinforcement fibre - MPa/$Tex_{(reinforcement)}$			
Pre-tension [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 present the highest “tenacity” followed by the braided fabrics reinforced by polyethylene.

Braided fabrics reinforced with polyethylene fibre present the highest values of extension at failure, followed by glass, carbon and sisal fibre reinforcements (Figure 6). The influence of pre-tensioning on extension is more significant. A decrease of pre-tensioning leads to a decrease on extension at failure of 30% for sisal reinforced braided fabrics and around 10% for carbon and polyethylene reinforced braided fabrics. Braided fabrics reinforced by glass fibre present an increase of extension at failure of about 4% as pre-tensioning increases.

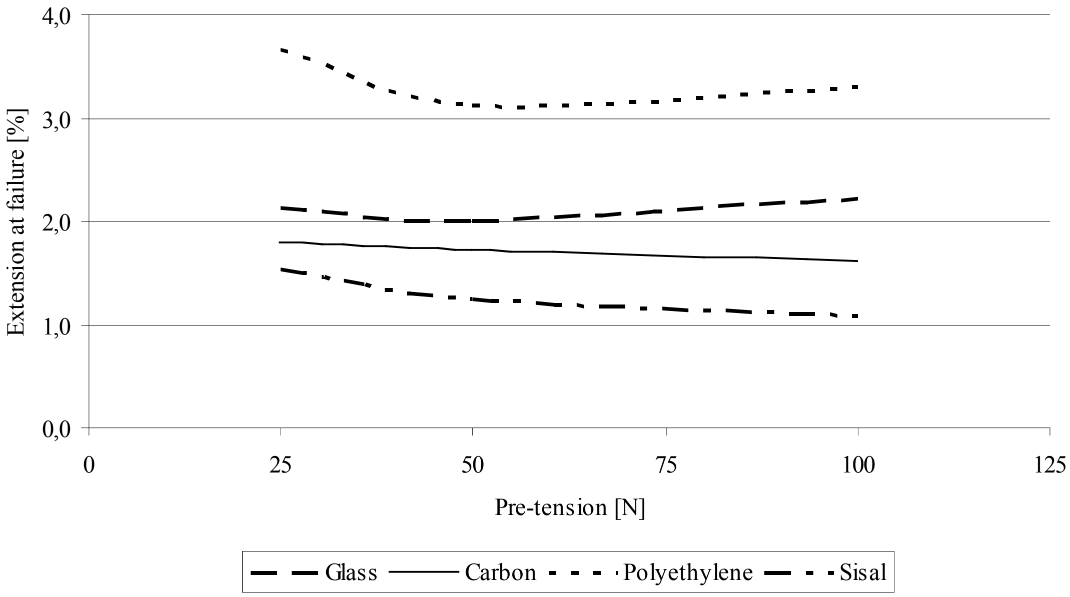

Figure 6 – Influence of initial pre-tension on extension at failure (mean values).

The modulus of elasticity increases 13 % and 17% respectively for the polyethylene and sisal fibre reinforced fabrics and 37% and 87% for the glass and carbon fibre reinforced ones when the pre-tension is increased from 25 to 100 N (Figure 7). The carbon reinforced fabrics present the highest modulus of elasticity, followed by glass, polyethylene and sisal fibre reinforced fabrics.

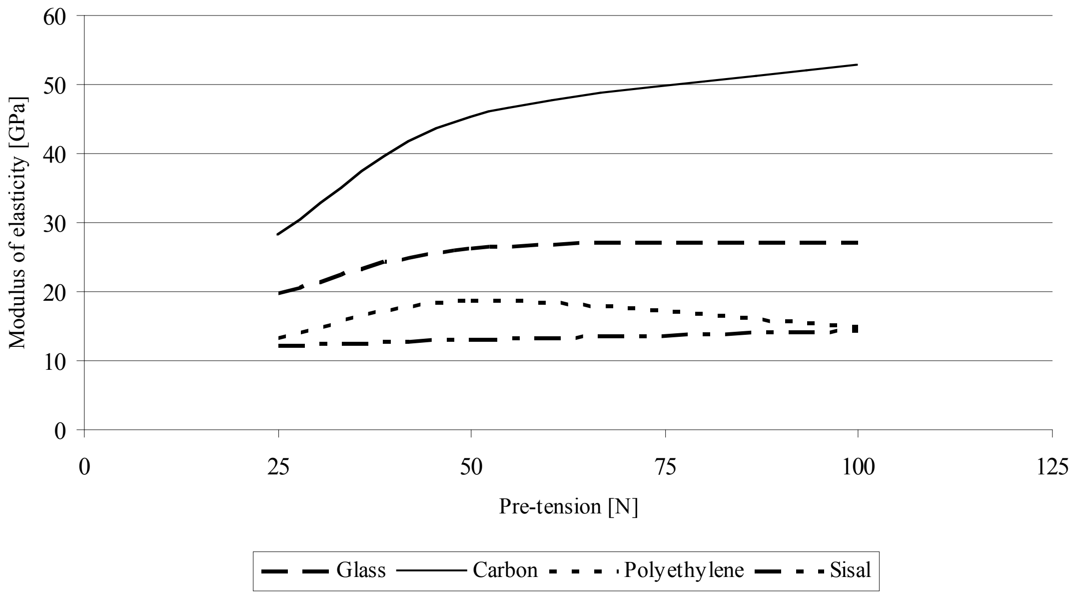

Figure 7 – Influence of initial pre-tension on modulus of elasticity (mean values).

The effect of initial pre-tensioning of the fabrics presents a significant influence on their modulus of elasticity, as can be seen by analysing the core reinforced braided fabrics tensile behaviour (Figure 8).

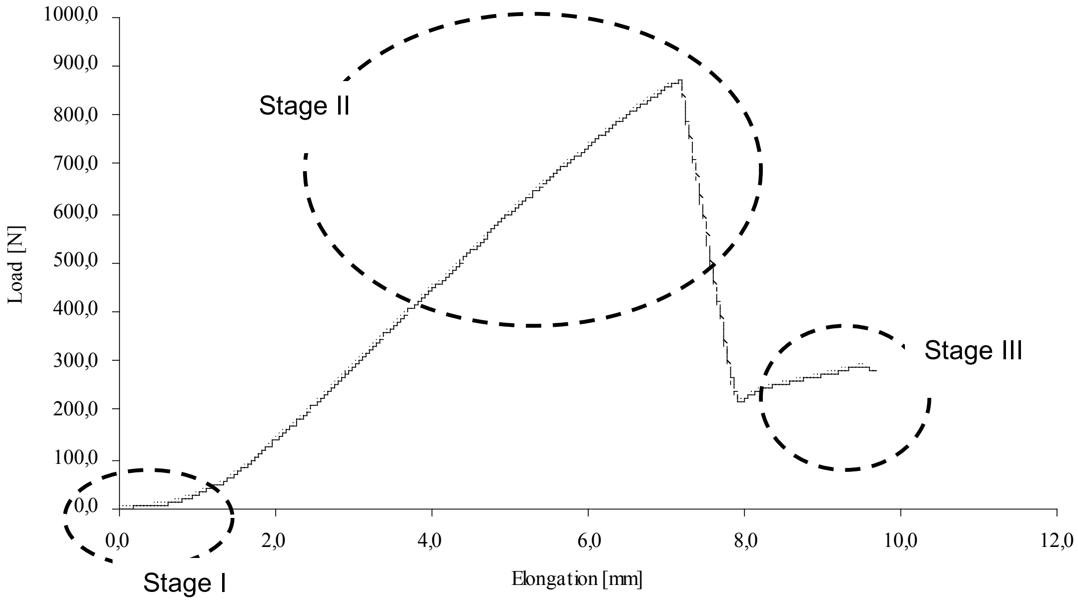

Figure 8 – Tensile behaviour of a core reinforced braided fabric.

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

Stage I – The load is borne by the core reinforced fibres; even though, the fibres are not yet completely straight.

Stage II – The reinforcement fibres are now completely straight and the load is borne by the core reinforced fibres. There is a significant increase in the load required to stretch the reinforcement fibres to the breaking point.

Stage III –The braided fabric starts to bare the load. Even though braided structures are characterized by having much better tensile properties comparatively to compressive ones, elongation is much higher than for fibre rovings.

Therefore, it is extremely important to assure that the core reinforced braided fabric presents all the reinforcement fibres completely straight. The influence of this factor on the ultimate tensile strength is not significant; however, the influence on the modulus of elasticity and on extension to failure is very significant and cannot be underestimated.

2. 4. Braided reinforced composite rods

The braided reinforced composite rods have been produced according to the procedure explained in previous studies [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 integrated as a simultaneous operation. During the curing period of the vinylester resin, neither the braided fabrics nor the reinforcement fibres were subjected to pre-tensioning. Bending and tensile tests were carried out on the composite rods, according to a procedure explained elsewhere [6 to 9]. During the tensile test the composite rods were subjected to a pre-load of 25N and 100N. Table 5 presents the mean value of the results of the tensile test carried out on the composite rods.

Table 5 – Tensile test results for composite rods (mean values).

Pre-tension [N]	Reinforcement fibre	Ultimate tensile stress [MPa]	Extension at failure [%]	Modulus of elasticity [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 fibre present the highest ultimate tensile stress, on both test conditions. Composite rods reinforced by glass fibre and polyethylene fibre present similar ultimate tensile stress on both test conditions, with slightly higher ultimate tensile stress when the composite rods are subjected to a pre-tension of 25N. The same results are attained with composite rods reinforced with sisal fibres.

Similar conclusions can be drawn in relation to extension at failure and modulus of elasticity. The best results are achieved with 25N pre-tension test conditions, and composite rods reinforced by carbon fibres, present significantly higher modulus of elasticity, followed by composite rods reinforced by glass and polyethylene fibres. Composite rods reinforced with sisal fibres present the lowest modulus of elasticity. Table 6 presents the test results for the bending tests carried out on composite rods.

Table 6 – Bending test results (mean values).

Reinforcement fibre	Bending stress [MPa]	Bending modulus [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 fibre present the highest bending stress, followed by composite rods reinforced with glass, polyethylene and sisal fibres. Similar conclusions can be drawn relatively to the bending modulus. Composite rod reinforced with carbon fibres, presents significant higher bending modulus, followed by composite rods reinforced by glass and polyethylene fibres. Composite rods reinforced with sisal fibres present the lowest bending modulus.

3. CONCLUSIONS

The geometry of the braided fabric structure was analysed. The influence of the braiding angle on the mechanical performance of core reinforced braided fabrics was studied. It was concluded that for a braided fabric structure there is a braiding angle that promotes the optimized mechanical performance of the core reinforced braided structure.

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

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

Braided fabrics reinforced with carbon fibres present the highest ultimate tensile stress and modulus of elasticity and one of the lowest extensions at failure values. Sisal reinforced braided fabrics present the lowest ultimate tensile stress, extension at failure and modulus of elasticity. Braided fabrics reinforced with glass and polyethylene fibres present similar mechanical properties. Similar conclusions can be drawn when analysing composite rods. Carbon reinforced composite rods present the highest bending stress and the highest bending modulus. It is the composite rod reinforced by sisal fibres that presents the lowest bending stress and the lowest bending modulus.

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 it is necessary to set a pre-tension on the reinforcement fibres to guarantee an optimized mechanical behaviour of core reinforced braided fabrics. This work also suggests that during the production of braided reinforced composite rods it is necessary to subject the reinforcement fibres to pre-tensioning, in order to set them completely straight within the composite rods. Otherwise, the mechanical properties of the composite material will be considerably hindered, as the resin may bare the initial load and fail before the load is transferred to the reinforcing fibres. Once the resin is cured, the reinforcement fibres of the composite rods can no longer be straightened.

When compared with the steel rebars currently used in the construction industry, composite rods reinforced by carbon, glass and polyethylene fibres present higher ultimate tensile stress. Current steel rebars, A235NL/R, A400NR/ER/EL and A500NR/ER/EL have values of ultimate tensile stress around 360 MPa, 460 MPa, and 550 MPa respectively [10]. Sisal reinforced composite rods present an ultimate tensile stress much lower than steel. Even though the ultimate tensile stress of carbon, glass and polyethylene fibre reinforced composite rods is higher than that of steel rebars, composite rods have a lower modulus of elasticity when compared with the 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 include means of pre-tensioning control of the reinforcement fibres during composite manufacturing. This will hopefully lead to the improvement of the mechanical performance of braided reinforced composite rods.

4. ACKNOWLEDGEMENTS

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