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BASALT FRP RODS ASSESSMENT AS AN ALTERNATIVE REINFORCEMENT FOR REINFORCED CONCRETE

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ABSTRACT

The consequences of global warming are becoming increasingly disastrous. Nowadays, our society has the responsibility of reducing the energy consumed in the building sector. In order to reduce this 40% of emissions, applying sustainable development criteria is fundamental throughout the life of materials in construction. More specifically, the use of steel corrugated bars or rods as reinforcement is the most widely used product in concrete reinforcement, and it is therefore important to reduce its climate impact. Basalt Fibre Reinforced Polymers (FRP) is a promising alternative to replace these steel reinforcements due to its high strength, low weight and high durability capabilities.

This work compares different rebars in sustainable terms in an initial phase. Four different materials are studied: steel, stainless steel, glass FRP and basalt FRP. To check and verify the different geometrical and mechanical properties, four rods of each material are tested in the laboratory. Finally, an analysis and comparison of various sustainability aspects is carried out. The aim of this research is to find out which reinforcing bar is the most sustainable and whether the basalt FRP rod is as optimal as it promises to be.

KEYWORDS

Basalt fiber reinforced polymer; BFRP; rods; concrete reinforcement; sustainable structures.

1. INTRODUCTION

The most common structural system in the world is reinforced and prestressed concrete, given its low cost per unit weight and formability (Koch et al. 2003). Corrosion is a natural process of deterioration of a metal due to its tendency to seek electrochemical equilibrium when in contact with its environment. Nowadays, it is one of the most common pathologies in structures, endangering their stability and generating high maintenance costs. Nevertheless, corrosion of the steel reinforcing material such as rods and strands leads to concrete cracking due to internal pressure caused by low-density iron oxide products (Val & Stewart 2003).

Epoxy-coating carbon steel and stainless-steel reinforcing products are common alternatives, but fiber-reinforced polymer (FRP) composites are becoming more frequently adopted as so-called "corrosion-resistant" concrete reinforced materials. The reasons are their excellent mechanical properties, low density and resistance to galvanic corrosion (Meier 2000). Numerous studies on FRP for structural reinforcement are reported every year, covering topics such as environmental durability (Tanks, Sharp & Harris 2017) and material mechanics (Ricciardi et al. 2021). Considering the time scale of service of life for a concrete structure, long term durability and reliability of the reinforcing materials will be extremely important in this research.

The most commonly used FRPs in construction are carbon (CFRP), aramid (AFRP), glass (GFRP) and basalt (BFRP), although their use as reinforcement in concrete is limited by the lack of data, design guidelines, standards or codes for their use. Basalt fibres have been used as reinforcement in concrete bridge deck slabs because of their improved corrosion resistance (Tharmarajah et al. 2010) and in geopolymer concrete (Li & Xu 2009). Hybrid glass-basalt FRP laminates performed equally as well as GFRP laminates when tested for column confinement (De Luca et al. 2011). Basalt FRP strengthened beams demonstrated better performance in comparison to glass FRP when subjected to elevated temperatures (Tan & Zhou 2011).

The composition of these elements is defined by a matrix as a continuous element, with limited mechanical properties, which acts as a binder providing cohesion to the reinforcements. Two main groups can be distinguished: thermosets and thermoplastics. The most commonly used matrices are polyester resins, vinyl ester resins and epoxy resins. In addition to the matrix, there is also the reinforcement, which is generally the fibres, responsible for providing the composition with optimum mechanical performance. It is essential to establish a synergy between the two components. In addition, there is the interface, the junction zone between the different phases of the material, which can be more important than the nature of the matrix and the mechanical properties of the reinforcement fibre of the material (Poveda 2012).

Basalt is one of the most commonly occurring rock types and basalt fibres possess significantly lower global warming potential than steel and synthetic fibres. Basalt fibres, which are drawn from basalt rocks and come at a relatively low cost, have recently gained more attention as an alternative to glass fibres due to having superior mechanical properties (Ali, Mohamed & Benmokrane 2020).

The literature on the use of basalt fibres in structural engineering applications is limited. FRP rods have excellent mechanical properties, are lightweight and have good chemical and corrosion resistance (Hollaway & Teng 2008). Some of the advantages these materials offer are high tensile strength and stiffness to weight ratio, their ability to resist corrosion and chemical attack, controllable thermal expansion, and higher damping and electromagnetic neutrality than other materials. These characteristics can also provide greater safety and a longer life cycle (Almerich 2010).

Due to FRPs are unidirectional materials having high tensile strength in the longitudinal direction and weak strength in the transverse direction, the existing technology of anchoring steel tendons becomes inapplicable in the case of FRP tendons, and the utilization of such fibre tendons has been linked to successful anchor systems design (Karbhari 1998). The relatively low strength of the BFRP rod in the transverse direction and the absence of an optimal anchor adopted for prestressing such type of FRP tendon make developing the anchor the first step for further investigations. This issue arises in the experimental phase in this research. The understanding of its behaviour is still limited, and the investigation of this material and its performance in different types of structures for testing becomes a necessity.

2. METHODOLOGY

One of the purposes of this work is to study, employing the analysis and comparison of the tests, the mechanical behavior of four types of corrugated bars of different materials for concrete reinforcement: steel, stainless steel, glass fibers and basalt fibers. This study is structured in two parts: firstly, a geometrical and weight study is carried out, and later on, tensile tests.

	Rm (MPa)	Rp 0,2% (MPa)	A (%)	Standard
Steel	>500	>550	>7,5	UNE-EN 10080
Stainless steel	>660	>600	>12	BS 6744
Glass FRP	>420	-	>1,2	UNE 6892
Basalt FRP	>310	-	>2	ACI 440.3R-04

Table 1. Propierties of the assessed materials. (Rm: elastic limit; Rp: tensile strength; A: elongation at maximum load)

The choice of materials is due to the ease of obtaining samples and the relevance in terms of mechanical aspects and sustainability. The reason for choosing 4 samples of each is to avoid dispersion of results, being a diameter of 6mm due to the availability of materials.
The steel rods type B 500 SD were chosen because it is the most traditional and usual. The stainless-steel rods were chosen for their great corrosion advantages. Technically it is expected to result from high strengths because of the cold rolling process. In the case of GFRP and BFRP, they are both competing with each other and they are relatively new, positioning themselves as promising alternatives to common concrete reinforcements. The properties of the assessed materials can be seen in (Table 1).

2.1. Geometrical and weight study

This study is done under the same regulation for all samples. The objective is to know the geometry of each of the samples because this is fundamental to their mechanical and adherence behavior. These data are also very useful for tensile tests. Shall be taken into account: real diameter, real mass, equivalent cross-sectional area, height of transverse corrugations, corrugation spacing and corrugation slope (Table 2).

2.2. Tensile test

Bars are subjected to axial tensile stress to failure, under the considerations laid down by ACI 440.3R-04 B.2 "*Test method for longitudinal tensile properties of FRP rods*" (American Concrete Institute 2004).
As tensile stress is the main stress that rods are subjected to, these tests indicate their structural behavior. The data obtained are the ultimate load (Fr), the maximum load (Fm) and the force-deformation diagram. From the previous data and the data obtained from the geometric and weight study, the conventional elastic limit, the tensile strength and the elongation can be obtained by calculation. These data will be used to carry out the analysis and comparison of the different samples.

3. RESULTS

3.1. Geometrical and weight study

Analyzing the results of these tests, the weight of the samples is the factor that shows the greatest dispersion between the different materials (Table 2). Because FRP elements weigh considerably less, the difficulty of assembly is reduced, facilitating both manual and technological work, with an impact on sustainable practices.
Physical adherence as such, would not occur optimally in the case of FRP materials, since this is mainly due to the corrugations, and these only present a helix shape around the bar, which by a simple blow is detached from it, causing the physical adherence to be less than optimal. This is also accentuated by observing the separation between the corrugations (Fig. 1).

Rods	Nominal diameter (mm)	Real diameter (mm)	Real mass (Kg/m)	Cross sectional area (mm^2)	Corrugation height (mm)	Corrugation separations (mm)	Corrugation inclination (º)
A1	6	5,816	0,218	27,76	0,383	4,35	B_1=70º
A2	6	5,87	0,217	27,74	0,383	4,40	B_1=68º
A3	6	5,93	0,218	27,76	0,316	4,35	B_1=66º
A4	6	5,92	0,218	27,79	0,383	4,40	B_1=64º
I1	6	5,93	0,215	27,39	0,50	5,20	B_1=65º
I2	6	5,93	0,214	27,26	0,55	5,10	B_1=63º
I3	6	5,93	0,215	27,38	0,53	5,10	B_1=62º
I4	6	5,92	0,215	27,39	0,56	5,10	B_1=67º
V1	6	5,88	0,040	27,15	0,16	15,20	B_1=55º
V2	6	5,80	0,050	26,42	0,33	19,80	B_1=47º
V3	6	5,74	0,049	25,88	0,30	17,40	B_1=49º
V4	6	5,77	0,050	26,19	0,13	17,40	B_1=49º
B1	6	7,11	0,083	39,77	0,58	16,00	B_1=61º
B2	6	7,05	0,082	39,03	0,71	15,80	B_1=60º
B3	6	7,15	0,085	40,15	0,51	15,80	B_1=60º
B4	6	6,78	0,080	36,10	0,50	15,60	B_1=58º

Table 2. Geometrical and wight test results. (A: steel; I: stainless steel; V: GFRP; B: BFRP)

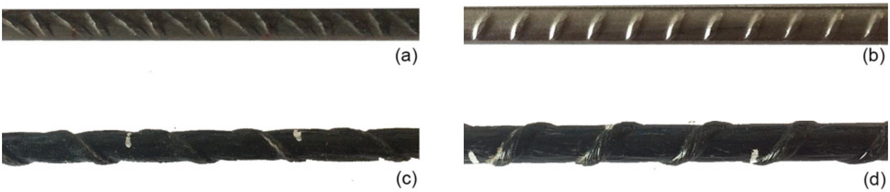

Figure 1. (a): steel rod; (b): stainless steel rod; (c): glass FRP rod; (d): basalt FRP rod

Rod	Distance (mm)	Rm (MPa)	Rp $_{0,2\%}$ (MPa)	A (%)
A1	483	661,38	569,88	25
A2	490	661,13	567,77	23,33
A3	498	668,94	578,89	23,33
A4	453	657,93	563,51	23,33
I1	505	958,01	941,94	30
I2	480	953,77	915,26	26,66
I3	487	961,28	950,32	25
I4	487	951,07	920,04	26,66

Table 3. Mechanical test results. (A: steel; I: stainless steel)

Rods	Rm (MPa)	$Rm_{,ck}$ (MPa)	$Rp_{0,2\%}$ (MPa)	Agt (%)	A (%)
A	662,22	649,68	570,01	11,97	23,74
I	956,03	944,30	931,89	8,36	27,08

Table 4. Average results and characteristic results of the tensile tests on steel and stainless-steel rods. (Rm: tensile strength; $Rm_{,ck}$: maximum characteristic tensile strength; $Rp_{0,2\%}$: conventional elastic limit; Agt: total elongation percentage maximum load; A: total elongation at break)

3.2. Tensile tests

- *Steel and stainless-steel rods*: all four samples had a typical development in each different material as can be seen in Table 3. Average results appear in Table 4.
- *GFRP rods*: One consideration to be taken into account when testing FRP corrugated bars is the protection of the ends with an anchorage system, as when they are gripped by the testing machine, due to their low transversal compression, the ends of the specimens will fail by crushing. For this reason, a precise design of the anchorages is necessary, whereby the anchorage length is crucial and depends on the adhesive behavior of the rebar. Due to the lack of resources and instruments, the elaboration of the necessary anchorages to carry out the test according to ACI 440.3C-04 was not possible. As expected, in the first test (V4), the failure of the test is caused by the slipping of the rod, due to the crushing of the specimen by compression of the clamp. In order to prevent the ends of the specimens from being completely crushed by the grips and to avoid a loss of cross-section, which would cause the test machine to show a null result, these ends are worked by hammering so that they are as flat as possible, facilitating the gripping of the grips (Fig. 2a). In Table 5 appear the tensile tests results on glass FRP rods.

Figure 2. (a) Worked end of a GFRP rod; (b) GFRP rod tensile test; (c) Tightening of the BFRP rod

Rod	V1	V2	V3	V4
Distance (mm)	469,00	483,00	489,00	490,00
Rm (MPa)	336,27	333,83	396,83	395,57
$Rp_{0,2\%}$ (MPa)	-	-	-	-
A (%)	0	0	0	0

Table 5. Tensile tests results on glass FRP rods. (Rm: tensile strength; $Rm_{,ck}$: maximum characteristic tensile strength; $Rp_{0,2\%}$: conventional elastic limit; A: total elongation at break)

Since the tests have not been carried out under the conditions recommended by ACI 440.3R-04, to carry out the analysis and comparison of results in an accurate manner, the values of the mechanical properties, from external tests made under all the precise considerations, shall be added. (Table 6). The force-deformation curves are not added because they do not provide information on the resistant capacity.

- *BFRP rods*: The solution used to be able to carry out the tests without compression breakage at the ends of the rods and their subsequent slippage is similar to that of the GFRP tests, although in this case, in addition to crushing the ends, part of the corrugations is eliminated. To work the ends of these rods, in addition to the use of a mallet, a squeeze is used in order to acquire an optimal grip (Fig. 2c). Table 7 shows the results of tensile tests on basalt FRP rods. The force-deformation curves are not added because they do not provide information on the resistant capacity.
  As before, to ensure better accuracy in the analysis of the results and comparison, in order to follow the standards, a test by an external institution is used. (Table 8)

Analyzing the results, the behavior of steel and stainless-steel rods follows an elastic-plastic behavior with a yield step, obtaining values close to those commonly known. It should be noted that the mechanical strengths obtained in the stainless-steel tests reach higher values due to the cold-rolling manufacturing process. On the other hand, in the FRP corrugated bars tests, not all of them reach breakage due to the slippage they suffer in the jaws. But can be affirmed, thanks to other company tests, that these have a behavior typical of composite materials, generating an elastic-linear force-extension diagram, where an elastic phase

Cross-sectional Area (mm^2)	Rm,$_{ck}$ (MPa)	Rp $_{0,2\%}$ (MPa)	A (%)
31,67	896	-	1,94

Table 6. Average results and characteristics characteristic results of the tensile test on glass FRP rods. Source: (Owens Corning Infrastructure Solutions LLC 2019)

Rod	B1	B2	B3	B4
Distance (mm)	389,00	398,00	411,00	421,00
Rm (MPa)	266,53	268,25	329,26	418,28
Rp $_{0,2\%}$ (MPa)	-	-	-	-
A (%)	0	0	0	0

Table 7. Tensile tests results on basalt FRP rods. (Rm: tensile strength; Rm,$_{ck}$: maximum characteristic tensile strength; Rp $_{0,2\%}$: conventional elastic limit; A: total elongation at break)

Cross-sectional Area (mm^2)	Rm,$_{ck}$ (MPa)	Rp $_{0,2\%}$ (MPa)	A (%)
41,176	907,7	-	2,148

Table 8. Average results and characteristics characteristic results of the tensile test on basalt FRP rods. Source: (Riga Technical University 2019)

is observed without having a plastic phase, determining the fragile behavior of the FRP materials. This behavior is quite the opposite of what is looking for: large deformations that generate warning capacity.

And although the tests themselves cannot be considered valid, the results obtained show high resistances for the little deformation suffered. These strengths are mainly due to its fiber structure, which allows it to absorb high tensile stresses in a direction parallel to the fiber arrangement. What is remarkable about these materials are the high mechanical strengths, values of around 900 MPa, shown by the external tests of these FRP.

The fact that the FRP rods suffer a compressive rupture due to the action of the jaws may seem to affect their compressive strength inside the concrete, but in reality, this does not determine their resistance to these stresses, since inside the concrete the compression will be uniform and distributed along the length of the rod, so it will not be subjected to such high forces.

As it has been already exposed, one of the most remarkable aspects is the high tensile strengths of stainless steel, however, the most optimal proposal in terms of weight-strength ratio is the one composed of FRP, obtaining very similar ratios in both glass fiber and basalt fiber rods.

4. SUSTAINABILITY

Sustainability in architecture addresses the negative environmental and social impacts of buildings by utilizing design methods, materials, energy and development spaces that aren't detrimental to the surrounding ecosystem or communities.

A sustainability study requires a life cycle analysis of each of the different materials. The comparison in terms of sustainability criteria between the different ones is represented in the following lines.

Both traditional steel and stainless steel have on a large-scale favorable aspects to be recycled – unless they are rusted - thanks to their capacity to maintain their properties, but the processes that make this possible entail a high energy consumption, which on the other hand are lower than those produced if recycling were not carried out. On the other hand, FRP materials do not have developed techniques that allow for optimal recycling, which is compounded by the high energy consumption needed to produce the raw materials, but this can be compensated by the great durability of these materials as concrete reinforcement. In addition, the resins used in the matrix are not sustainable materials, at the moment.

Furthermore, one of the phases of the life cycle that most interferes with the sustainable development of these materials is the transport of these materials. The underdevelopment of the FRP reinforcement industry means that the origin of these products is unlikely to be local. In addition to their inability to be recycled optimally leads to an increase in the transport of the materials.

The low weight of FRP corrugated products together with the weight/strength ratios compared to steel and stainless-steel means that the transport of these products is reduced, as equal strength means a significant quantitative difference in weight (Table 9).

	Steel	Stainless Steel	GFRP	BFRP
Weigh/Strength	$3{,}28\cdot10^{-4}$	$2{,}24\cdot10^{-4}$	$6{,}64\cdot10^{-5}$	$8{,}39\cdot10^{-5}$

Table 9. Weigh/strength rods relation

Compared with the prices of corrugated FRP, it is shown that these materials have the same strength and durability, but have a lower selling price, which is boosted by their weight/strength ratio, which means that the cost in other phases of the project is lower. Even so, it should be noted that the little technological development to date of this type of materials in structural functions means that other processes such as recycling or production entail other types of costs. However, the sustainable potential of these materials opens up numerous avenues for research and development.

It is fair to mention the durability of non-metallic materials in terms of non-corrosion, that is probably the strongest point. Indeed, this is not the case for stainless steel rods, but the price of these rebars is much higher for the same mechanical resistance. For that reason, for the same price we get more durability in terms of non-corrosion and strength on the basalt fibre reinforced polymer side.

Talking about energy content and gas emissions, it is difficult to compare the tangible amount of environmental impact as all rods exercise unsustainable practices during their manufacture in one way or another. The high energy consumption of this industry and the emissions and gas emissions into the atmosphere are more than evident.

5. CONCLUSIONS

Traditional materials, steel and stainless steel have high energy consumption and high waste production. In contrast, the strength of FRP materials lies in their development potential, which to date is only a small part of what is expected. Their inherent characteristics such as high strength, low weight and high durability capabilities open up a new path towards structures with higher mechanical and environmental resistance using less material than traditional structures, and also at lower economic costs. However, this will require more research and studies to encourage innovation in all processes related to these materials, such as production, recycling and safety. Other improvement key areas that nowadays are not working well are the poor adherence of the corrugations, brittle fracture without deformation described by an elastic-linear diagram without a plastic phase, showing a brittle behavior without deformations at break and lastly, transverse compression fracture due to some anchorages.

It can be concluded that low weights of FRP materials linked to their high strengths offer options for the development of the design and sustainable character of structures, taking into account their difficulty of recycling in favor of improved durability. FRP reinforcement elements are still at a premature stage of development, in the absence of standards, design guidelines and research studies on their behavior in different environments, to obtain sufficient data to establish a fully reliable basis for their use as concrete reinforcement. It can be argued that there is no ideal sustainable rod that meets all the requirements above the rest. In any case, it should be as close as possible to these requirements, balancing all the sustainable factors together and taking into consideration the promising development of non-metallic alternatives.

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