Comparative analysis between carbon, glass and aramid fibers for structural reinforcement in reinforced concrete elements

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Abstract

This article presents a comparative study between the physical and mechanical properties of carbon, glass and aramid fibers, in their application as structural reinforcement in reinforced concrete elements. This study consists of an analysis of a bibliographical review in which we sought to evaluate the main characteristics of these materials, namely: tensile strength, compressive strength, rigidity, fatigue strength, thermal expansion, moisture resistance, corrosion resistance and cost. It is observed that for a good result in reinforcement with application of fibers, it is necessary to know the material, the element that will be reinforced and the desired properties.

Keywords: Fibers; Structural reinforcement; Properties.

1. Introduction

From the first appropriations and combinations of materials adopted to meet the need for shelter or support for human activities, that is, from the use of construction materials par excellence - such as soil, water, rock, wood and several other elements of mineral and organic origin – the enormous diversity of components available today to be used in civil construction was developed [1].

In Brazil, after 1930, concrete became a symbol of national technological development, used since then in the main works in the country. Along with other factors that contributed to the increase in the use of concrete in civil construction, the discovery of the various specific properties of the new material led to a great development of its technology, especially from the 1930s onwards. explore and value the possibilities of the new material, showing its specificities, reinforced, at the same time, with the emergence of modern Brazilian architecture, when reinforced concrete started to play an important role [1].

According to [2], the consolidation of reinforced concrete as one of the most important civil construction techniques took place in the 20th century. The author states that reinforced concrete structures are the most widespread in Brazil, surpassing by a large margin those made of steel and wood in urban environments, mainly due to their versatility and their relatively low production cost.

However, [3] states that reinforced concrete also ages, and it is necessary to provide for its maintenance throughout the useful life of the structure. According to the same author, there was less concern in the past with questions of the durability of structures, due to this, today we are witnessing an increase in degraded structures that impair the appearance, safety and functionality of the building, requiring repair, rehabilitation and reinforcement, in order to respond to current requirements or any planned changes in use.

According to [4], in general, structural reinforcement interventions can occur both throughout the service life and in the construction stages, where errors commonly occur. This author also exposes that, among the causes for the need for reinforcement, failures in the execution or in the project, use of inappropriate material, change in the use of a certain area with the increase of the load of use, incompatibility of projects, among others, can be pointed out. miscellaneous causes.

For the reinforcement of cementitious matrices, there are numerous viable fibers. In addition to natural fibers (cotton, sisal, banana and coconut), of vegetable or mineral origin (asbestos), numerous fibrous materials have been created in recent years from the oil chain. These fibers have very interesting characteristics and are already widely exploited in the chemical, naval and aerospace industries. Combined with other man-made materials, they form the most important group of fibers, the synthetic fibers. Examples of synthetic fibers are mainly carbon, aramid and glass fibers [5].

Carbon fibers, as stated by [6], have good strength, light weight and corrosion resistance, providing a longer service life to the reinforcement of the structure. For [7], glass fibers have advantages such as: low cost, high resistance to impact and corrosion. As expected benefits of incorporating aramid into concrete, there is an increase in load capacity, restriction of deformation, increase in ductility, durability, among others [3].

Therefore, the present work carried out a comparative study on the efficiency of three types of fibers used for structural reinforcement: carbon, glass and aramid fibers (Kevlar). Thus, the main characteristics of these materials were compared, in relation to tensile strength, compressive strength, rigidity; resistance to fatigue, thermal expansion, resistance to humidity, resistance to corrosion and cost, based on studies already carried out on these reinforcement methods in reinforced concrete structures.

2. Methodology

The present article is structured in a bibliographical revision, of analytical and comparative character regarding carbon, glass and aramid fibers, for structural reinforcement in reinforced concrete elements. The proposed study is based mainly on scientific articles, master's dissertations, doctoral theses and books.

3. Results and Discussion

3.1 Use of composite materials for structural reinforcement

Composites are materials whose structure is constituted by the combination of two or more non-soluble products. One of the products is the reinforcing material and the other is the matrix. The matrix surrounds the reinforcement, and may have additions in its composition, such as fillers, which modify and can improve the its properties. An example of composite material is concrete [8].

Polymeric composite materials, or fiber-reinforced plastics, are basically composed of high-strength fibers wrapped in a polymeric matrix. These fibers must be selected according to the resistance, rigidity and durability required. Thus, polymeric composite materials can be used to repair and reinforce conventional concrete structures and also in the design of new structures [8].

According to [9], the need to reinforce structures arises whenever it is necessary to correct anomalies in design, execution, use or the need to change the purpose of the building.

[10] explains that, for the treatment of a defective construction or one that has undergone alterations due to its use, the correct diagnosis of the existing pathologies must first be made. For each case, there will be at least one method to perform the repair.

With the structural reinforcement, the problem of increasing the weight of the section could arise and so synthetic materials began to be used, materials whose main advantages are non-corrosion, high resistance and lightness, providing the structure with the desired resistance and an overload not accentuated, and the most used synthetic material is carbon [7].

For [11], the choice between a type of fiber and a matrix fundamentally depends on the application that will be given to the composite material: high mechanical characteristics, resistance to high temperature, resistance to corrosion, etc. In addition, according to [9], factors such as environmental characteristics, durability and application time must be taken into account, in addition to meeting structural safety requirements.

Cost in many cases can also be a factor in choosing between one component or another. The compatibility between fibers and matrices must also be observed [11].

In Figure 1, it is possible to visualize the most recurrent types of fibers for structural reinforcement, according to Sousa (2008), they are: carbon fibers (a), glass fibers (b) and aramid fibers (c).

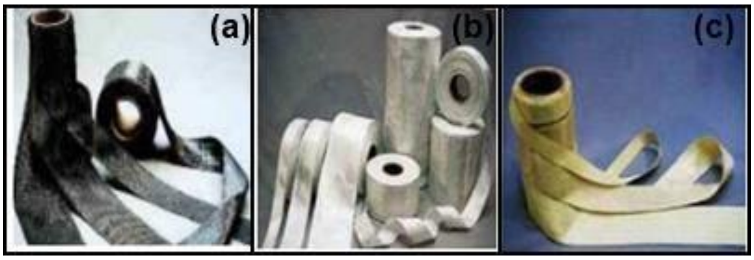


Figure 1. Fibers used for structural reinforcement, carbon fibers (a), glass fibers (b) and aramid fibers (c)

3.1.1 Carbon Fibers

The use of carbon fibers was first applied in the aeronautical, aerospace, automotive, naval and war industries. The use of this technique as a structural reinforcement meant a technological evolution for civil engineering, which has been seeking the application of new materials, with increasingly noble mechanical and chemical properties. Carbon fibers have been widely used in structures of bridges, viaducts, in the reinforcement of pillars, in beams subjected to bending and shear stresses and in bending slabs [12].

Carbon fibers originate from heat treatment (carbonization) of organic predecessor fibers such as polyacrylonitrile (PAN) or based on petroleum or coal tar (Pitch) in an inert environment and also through rayon fibers . The production process consists of the oxidation of these fibers, followed by processing at high temperatures (ranging from 1,000°C to 1,500°C). At the end of this process, the fibers have carbon atoms perfectly aligned along the precursor fiber, this characteristic gives the final product an extraordinary mechanical resistance [11].

Carbon fibers generally have a dark color and during their manufacturing process they can be manipulated in order to obtain higher resistance and modulus of elasticity. Fiber filaments can be produced in specific orientations, such as modifying critical stages of the production process. The higher the temperature in the manufacturing process, the greater the modulus of elasticity of the fibers [13]. However, according to the same author, the use of higher temperatures causes a reduction in tensile strength.

According to [8], carbon fibers have the following advantages: high stiffness and resistance to all types of chemical attacks (due to carbon being an inert material), good behavior in relation to fatigue, thermal and rheological variation, and little weight. Table 1 shows the main advantages and disadvantages of carbon fibers.

Table 1 – Main characteristics of carbon fibers

ADVANTAGES	DISADVANTAGES
Excellent mechanical characteristics	Reduced impact resistance
High modulus of elasticity longitudinal	High thermal conductivity
Low specific mass	Brittle fracture
High electrical conductivity	Low deformation before fracture
High dimensional stability	Low compressive strength
Low coefficient of thermal expansion	High cost
Good behavior at high temperatures (without oxygen)	

3.1.2 Glass Fibers

The production of glass fibers began in ancient Syria, Greece and Egypt. At approximately 250 BC, craftsmen began to produce the fibers through a heated glass rod to apply as relief on the surface of finished products. Commercially, fiberglass began to be developed in 1939, during the 2nd World War, with the aim of providing rigidity and lightness to military equipment.

According to [14], what is used in this context, “fiberglass”, consists of a plastic resin matrix composite, reinforced by embedded glass fibers. According to [4] glass fibers are made with varied compositions of different chemical elements, and because glass is a fluid material, it allows a better ability to adapt to dynamic loads.

Still according to [4], composites formed with glass fibers receive the terminology GFRP (glass fiber reinforced polymer) and are divided into:

- **E-Glass**: Its chemical formulation results in great resistance to corrosion by most acids;
- **S-Glass**: It is the most expensive glass fiber, and its production is the result of a specific quality control, meeting certain procedures and specifications of the military area;
- **C-Glass**: It is often used in chemical industries where contact with highly corrosive acids is required.

The advantages and disadvantages of this material are shown in Table 2.

Table 2 – Main characteristics of glass fibers.

ADVANTAGES	DISADVANTAGES
Good tensile and compressive strength	Reduced modulus of elasticity
Low cost compared to other fibers	High specific mass
High chemical resistance	Abrasion sensitivity
High fire resistance	Sensitivity to high temperatures
Good acoustic, thermal and electrical insulation properties	Low fatigue resistance

3.1.3 Aramid Fibers

Aramid fibers, or Kevlar, are composed of synthetic aromatic organic materials, consisting of carbon, hydrogen, oxygen and nitrogen, resulting from the extrusion and drawing of a type of nylon, whose molecular structure is formed by benzene and aramid chains [8].

Aramid fiber is very similar to carbon fiber. However, it mainly demands quality in the workmanship for the application and preparation of the surfaces [10]. This fiber, according to [13], can be found in different forms and with different cross sections.

According to [10], because aramid fiber does not conduct electricity, it is ideal for underwater application and work. According to the same author, the composite formed by Kevlar fiber and epoxy becomes the only option when you want to make reinforcements next to transmission or communication lines, not offering, on the other hand, electromagnetic interference to radio waves and instrumentation.

Characterized by having high mechanical strength, high dimensional stability, relatively high modulus of elasticity and low density (compared to carbon and glass fibers), it is currently widely used as reinforcement in high-performance composites. [8] argue that this fiber has the advantages of low density and retraction, and high resistance to traction and impact.

Table 3 exposes the main advantages and disadvantages associated with the use of this material.

Table 3 – Main characteristics of aramid fibers

ADVANTAGES	DISADVANTAGES
Low specific mass	Low compressive strengths
High tensile strength	Slow degradation under light (UV)
High impact resistance	High moisture absorption
Low electrical conductivity	Relatively high cost
Good chemical resistance (except concentrated acids and bases)	Poor adhesion to most polymer matrices (resins)
High abrasion resistance	Poor chemical resistance to concentrated strong acids
Excellent behavior under high service temperatures	

3.2 Comparative analysis of carbon, glass and aramid fibers

In the elaboration of a structural component in composite material, an attempt is made to optimize the use of the mechanical properties associated with fibrous reinforcements. One can consider a structure under the action of certain loads, such as static, dynamic loads or even combined efforts, the components that compose it have to be able to perform actions in accordance with the conditions foreseen or established in projects [12].

According to [14], the selection of reinforcements always takes into account aspects ranging from the cost of these materials to the intended performance and manufacturing technique. For [3] the choice of fiber must take into account the environment to which the reinforcement will be exposed and the load increment demanded by the structure. In addition, for this author, the direct and indirect costs of each system must be evaluated, resulting in a choice that reconciles costs and structural needs.

Thus, Table 4 presents the results of the comparison between carbon, glass and aramid fibers and classifies them as poor, fair, good and excellent, in relation to tensile strength, compression, fatigue, humidity and thermal insulation.

Chart 4 – Comparison of performance between carbon, glass and aramid fibers.

CHARACTERISTICS	FIBERS		
	CARBON	GLASS	ARAMID
Traction resistance	Excellent	Good	Excellent
Compressive strength	Excellent	Good	Regular
Rigidity	Excellent	Good	Good
Fatigue resistance	Excellent	Bad	Regular
Thermal expansion	Bad	Excellent	Bad
Moisture resistance	Excellent	Regular	Regular
Corrosion resistance	Bad	Excellent	Excellent
Cost	High	low	medium

3.2.1 Tensile strength

According to [5], the three fibers compared in this article (carbon, vibra and aramid) feature high tensile strength.

In relation to carbon fiber, [7] emphasizes as one of its advantages a tensile strength up to ten times greater than that of steel in the use of fiber in composites, becoming five times lighter than the same. Machado (2002) states that a carbon fiber composite system can reach up to 3,800 MPa of tensile strength. Meneghetti et al. (2010), in their studies obtained the value of 3,400 MPa for the tensile strength of carbon fibers.

According to [4], glass fibers, in their manufacture, are subjected to surface treatments, which vary according to the desired properties for the material, therefore, they can be classified into: A, E, S and R, according to with its composition and application.

The type a fiber, strongly alkaline, was replaced by the type E fiber, a borosilicate glass with low amounts of alkaline compounds. This type of fiber predominates in polymer matrix composites because of its high electrical insulation properties, good resistance to moisture and high mechanical properties. Type S glass fiber is characterized by greater heat resistance, good tensile strength and high Young's modulus, but is more expensive. Other special glass fibers, such as AR or R, have better chemical resistance [4]. [5], the tensile strength value of glass fibers is 1,517 MPa.

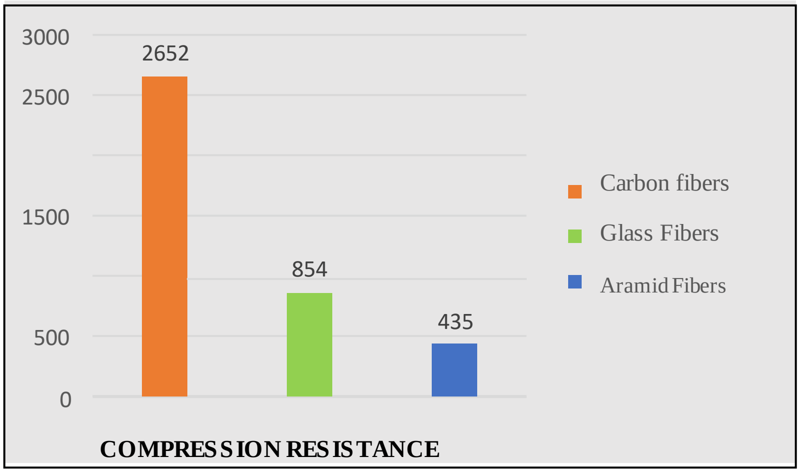
Aramid, in turn, being an organic fiber, in aromatic polyamide, has very high tensile strength. Since the addition in an epoxy matrix, it promotes an extraordinary increase in resistance to flexion, traction and impact. Offering a design tensile strength of 2,131 MPa [10], close to the value found by [4], of 2,173 MPa.

3.2.2 Compressive strength

Studies point out that in fiber reinforcement, the compressive behavior (strength, modulus of elasticity, specific deformation relative to maximum tension) is not as improved as the tensile and bending behavior (Medeiros, 2012). In this sense, the aramid fiber, even when stressed at relatively low tension levels, presents a non-linear behavior in compression. Corresponding to only 20% of its tensile strength, which disadvantages the aramid fiber compared to the use of other fibers. In general, carbon and glass fibers, when subjected to compressive stresses, present superior performance in reinforcing structural elements [8].

According to [7], compared to tensile strength, carbon fiber has a compressive strength of 78%, glass fiber 55% and aramid fiber 20%. Based on the statement by [7], Graph 1 represents the compressive strength values of the fibers, based on the tensile strength values assigned by [5].

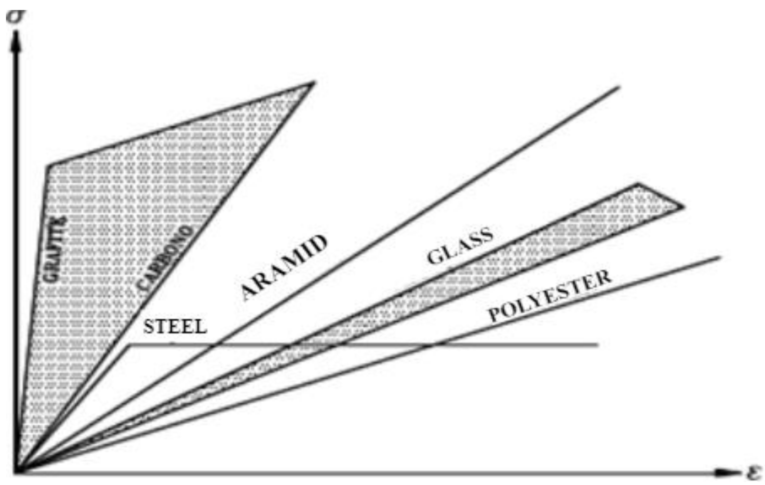
Graph 1- Strengths to axial compression of fiber-based polymers (Mpa).



3.2.3 Rigidity

The stiffness of a material is measured according to its modulus of elasticity, thus, if the material exhibits a high value for this parameter, it means that a high mechanical stress will be required to deform it.

According to [11], the thermal fiber production process confers extraordinary mechanical resistance to the final product, as can be seen in Graph 2.



Graph 2 - Diagram tension X deformation of the fibers

Fiber production is based on the oxidation of precursor fibers, followed by processing at high temperatures (for carbon fibers they range from 1,000°C to 1,500°C, for graphite fibers it reaches around 3,000°C). The higher the temperature at which the industry process is carried out, the greater the modulus of elasticity of the resulting material [11].

3.2.4 Fatigue resistance

From an engineering point of view, fatigue is understood as a failure mode that involves the formation and progressive growth of a crack in any structural element subjected to time-varying loading. This phenomenon occurs even when the maximum load amplitude induces stresses well below the static resistance of the material used [7].

It can be considered that reinforcements with carbon fibers favor the resistance to fatigue of the reinforced elements, since they provide a reduction in cracking and improve the distribution of cracks along the element, before failure [12].

[5] made test specimens, produced from three fiber blankets: carbon, glass and aramid, and two epoxy-based, two-component adhesive formulations, selected according to the recommendations of the manufacturers of the fibers. The specimens originating from these composites were cut to dimensions of 250 mm x 400 mm and subjected to cyclic tensile loads at a frequency of 5 Hz until failure. They found that the maximum applied load varied in the range of 0.45 to 0.80 of the ultimate tensile stress, always maintaining the ratio R=0.1 (ratio between the minimum and maximum load). The results showed that carbon fiber has the best fatigue performance, followed by aramid and glass. For the aforementioned author, the inferior performance exhibited by the glass fibers may be related to the phenomenon of rupture of the filaments that make up the composite right at the beginning of the loading, causing the matrix reinforcement effect to be lost, impairing the mechanical characteristics of the material set.

3.2.5 Thermal expansion

The coefficients of thermal expansion of polymeric composites differ depending on the type of resin, the type of fibers, the volumetric percentage of fibers and their orientation in the composite [6].

According to [6], in the direction parallel to the fibers, composites of resins and aramid fibers contract with increasing temperature, those of glass fibers have a coefficient of thermal expansion similar to that of concrete and those of carbon fibers have this coefficient almost zero.

According to [9], although the thermal expansion coefficients of resins and adhesives should also be considered when evaluating the application of a fiber-reinforced polymer in concrete structures, fiberglass reinforcements seem to be more suitable for use in these structures, due to the similarity in the coefficients of thermal expansion of glass fibers and concrete.

As for their thermal behavior, carbon fibers have a coefficient of longitudinal thermal expansion of a negative value (about $-10-6/°C$). That is, with an increase in temperature, the fiber retracts and with a reduction in temperature, it expands. This characteristic can be harmful since concrete has a coefficient of the same order, however positive, deforming in the opposite way to the fiber with thermal variation [6].

3.2.6 Moisture resistance

According to [3], water absorption is a property that must be considered, since most fibers have a certain porosity and are susceptible to volumetric or chemical variations induced by exposure to water.

The presence of moisture can cause substantial losses in the physical properties of composites, when their component materials have high water retention rates. Carbon fibers have low water retention and therefore can be considered as the least affected by the presence of moisture. In contrast, aramid and glass fibers show high water retention. In view of this, its use is more indicated for environments where the levels of humidity or water vapor are reduced [3].

Degradation of glass fibers due to the presence of moisture is initiated by the extraction of ions from the fiber by water. These ions combine with water molecules, forming bases that attack the glass fibers, which can significantly affect their resistance [7].

On the other hand, Aramid fibers, according to [7], absorb more than 13% of moisture by weight, which can result in a detrimental effect on tensile strength and can also affect the fiber-matrix interface.

3.2.7 Corrosion resistance

Corrosion resistance is an essential feature to ensure the durability of reinforced structures. In this criterion, carbon fiber is at a disadvantage compared to the others. Carbon fibers are conductive and can cause galvanic corrosion when in contact with the armature [7].

To avoid the occurrence of the corrosion process, it is extremely important that the designer of the reinforcement system pays attention, so that the direct contact of the reinforcement with the steel is avoided (Perelles et al., 2013). [7], also recommends that if it is not possible to avoid contact between the reinforcement and the reinforcement, the use of an enveloping resin matrix avoids the problem in situations where the reinforcement is molded in situ.

With regard to glass and aramid fibers, both are insulators and do not transmit electrical currents, which prevents the electrochemical corrosion process [7].

3.2.8 Cost

Carbon fiber, according to [9], contains the best combination of mechanical properties, but is also more expensive than fiberglass and aramid. It corroborates what was exposed by [5], that the higher the modulus of elasticity, the higher the cost of the material.

Glass fibers have a much lower cost than carbon and aramid fibers. However, it should be noted that to achieve the same level of reinforcement dimensioned with carbon fiber using fiberglass, it is necessary to use a much larger amount of fiberglass in relation to the amount of carbon fiber used. The use of a greater amount of fiber, in turn, requires the use of more resin or adhesive and consumes more hours of work, increasing the cost of using the system. Therefore, only the cost-benefit analysis regarding the use of each reinforcement system will allow the choice of the most suitable fiber to form the composite [12].

4. Conclusion

Structural reinforcement with fibers has been used more and more. Its use is given mainly by aspects such as: lack of maintenance throughout the useful life of the construction; human failures that may occur in design and/or construction stages; changes in the purpose of the buildings, according to the needs of the owner, which can increase the loads required by the structure. Furthermore, reinforced concrete structures have limited durability, and tend to fail and lose strength over time (Pivatto, 2014).

In this way, the use of fibers reinforcement becomes relevant because it is a rehabilitation of the structure, whose main purpose is to guarantee the functionality and safety of the building, also avoiding the appearance of pathologies.

In the present work, the characteristics, advantages and disadvantages of the main fibers used for structural reinforcement in reinforced concrete structures were presented.

Carbon fiber, for example, despite presenting excellent behavior in most of the characteristics analyzed, is not indicated for places where it will be subject to thermal expansion. In the same way, aramid fibers should not be used in places where they will suffer great thermal expansion, however they have excellent behavior when requested to traction. Glass fibers, on the other hand, can be used in places conducive to thermal expansion, but they are not very resistant to fatigue.

However, it is possible to infer that the choice of material to be used for reinforcement must take into account not only the cost, one must also consider the conditions of the structures to be reinforced, in addition to aspects to which they will be subject, such as humidity, temperature , etc., which are specific to each project.

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