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Concrete reinforcement using composite fiberglass-based materials

Reforço de concreto com materiais compósitos à base de fibra de vidro

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Abstract

Numerous existing structures, both old and new, have serious load-bearing capacity issues, which, in some cases, could endanger the safety of their users. In fact, we can say that these structures are nearing (or have already reached) the end of their useful lives, necessitating the need to find technical and financial solutions to renovate them as efficiently as possible. Many reinforced concrete bridges experience advanced states of deterioration as a result of extended exposure to hostile environments or even continuously rising use loads. Additionally, since the time of their construction, the technical standards used for the design and dimensioning of the old structures have had to be updated. As a result, some structural components that are still in use do not adhere to the standards for response to loads. In fact, it is frequently less expensive to reinforce the structural components of buildings than to perform a full reconstruction, especially now that, thanks to technological advancements, a variety of reinforcement techniques are still available and their costs are decreasing. One such technique involves externally reinforcing reinforced concrete elements with composite materials because of their superior strength-to-weight ratio and resistance to abrasion. Additionally, these composite materials can be utilized for column containment as well as shear and bending reinforcement for beams. This study aims to evaluate the impact of glass fibers on the general behavior of concrete, in particular on its resistance, deformations, and ductility, using FRP: Fiber-reinforced plastics are materials generally formed of two main and distinct elements: the fiber, "made from glass," and the matrix, "an epoxy resin that allows the transfer of loads between the fibers. The results of the specimens' cyclic loading tests attest to the significance of the contribution that concrete specimen confinement with FRP can make in terms of deformation and resistance to compression after the completion of static loading tests. However, these tests on the specimens' ability to withstand loading and unloading cycles reveal a very significant improvement.

Keywords: Concrete reinforcement. Composite materials. Fiberglass. Deformation. Compressive strength.

Resumo

Numerosas estruturas existentes, tanto antigas como novas, apresentam sérios problemas de capacidade de carga, que, em alguns casos, podem pôr em perigo a segurança dos seus utilizadores. Com efeito, podemos afirmar que estas estruturas estão próximas (ou já atingiram) o fim da sua vida útil, sendo necessária a procura de soluções técnicas e financeiras para as renovar da forma mais eficiente possível. Muitas pontes de concreto armado experimentam estados avançados de deterioração como resultado da exposição prolongada a ambientes hostis ou mesmo de cargas de uso continuamente crescentes. Além disso, desde a sua construção, as normas técnicas utilizadas para o projeto e dimensionamento das antigas estruturas tiveram que ser atualizadas. Como resultado, alguns componentes estruturais que ainda estão em uso não atendem aos padrões de resposta a cargas. Na verdade, é frequentemente mais barato reforçar os componentes estruturais dos edifícios do que realizar uma reconstrução completa, especialmente agora que, graças aos avanços tecnológicos, uma variedade de técnicas de reforço ainda estão disponíveis e os seus custos estão a diminuir. Uma dessas técnicas envolve o reforço externo de elementos de concreto armado com materiais compósitos devido à sua superior relação resistência-peso e resistência à abrasão. Além disso, esses materiais compósitos podem ser utilizados para contenção de pilares, bem como reforço de cisalhamento e flexão para vigas. Este estudo tem como objetivo avaliar o impacto das fibras de vidro no comportamento geral do concreto, em particular na sua resistência, deformações e ductilidade, utilizando FRP: Os plásticos reforçados com fibras são materiais geralmente formados por dois elementos principais e distintos: a fibra, " feito de vidro", e a matriz, "uma resina epóxi que permite a transferência de cargas entre as fibras. Os resultados dos ensaios de carregamento cíclico dos corpos de prova atestam a importância da contribuição que o confinamento de corpos de prova de concreto com FRP pode dar em termos de deformação e resistência à compressão após a realização dos ensaios de carga estática. No entanto, estes ensaios sobre a capacidade dos corpos de prova em suportar ciclos de carga e descarga revelam uma melhoria muito significativa.

Palavras-chave: Reforço de concreto. Materiais compostos. Fibra de vidro. Deformação. Força compressiva.

1. Introduction

Numerous existing structures, both old and new, have serious load-bearing capacity issues, which, in some cases, could endanger the safety of their users. In fact, we can say that these structures are nearing (or have already reached) the end of their useful lives, necessitating the need to find technical and financial solutions to renovate them as efficiently as possible. She. Many reinforced concrete bridges experience advanced states of deterioration as a result of extended exposure to hostile environments or even continuously rising use loads. Additionally, since the time of their construction, the technical standards used for the design and dimensioning of the old structures had to be updated. As a result, some structural components that are still in use do not adhere to the standards for response to loads (Golewski, 2023).

In most countries, 30% of bridges built before 2002 are considered damaged, according to statistics. It is even noted that some bridges and viaducts support up to 40% higher loads than those that had their initial dimensions (Martucci *et al.*, 2023; De Domenico *et al.*,2022). For this reason, it seems clear that we should not focus only on simple fixes. Instead, we should look for ways to make these structures stronger through reinforcement, which can also be used to make reinforced concrete structures last longer (Wagner *et al.*, 2022; Siddika *et al.*, 2020).

In fact, it is often less expensive to reinforce the structural parts of a building than to rebuild it from scratch. This is especially true now that technology is getting better, there are more ways to reinforce structures, and prices are getting lower. One example is the external reinforcement of reinforced concrete elements with composite materials, which are strong for their weight and resistant to corrosion. In addition, these composite materials can be used both for shear and bending reinforcement for beams and for column containment (Siddika *et al.*, 2020).

Fiber Reinforced Plastics are materials generally made up of two main and distinct elements: the fiber and the matrix. The fibers are made from one of the following types: Carbon, glass, or aramid. The matrix is an epoxy resin and allows the transfer of loads between the fibers, which improves the properties of the matrix in the long and short term and makes it possible to reduce the effects of shrinkage and creep. The fibers have the advantage of being very long in continuous form, which is ideal for civil engineering applications. As they can be placed in one or more directions inside the matrix (Berthet *et al*., 2005).

These fiber-reinforced plastics are manufactured in various forms (thin sheets, bars, profiles, etc.), and each product is suitable for a very specific use in the field of construction. Their properties, such as a high strength-to-weight ratio and excellent resistance to electrochemical corrosion, make these products highly sought-after materials for structural applications. This demonstrates how much research is needed to better understand their properties and promote their use in the field of construction.

In this study we study the benefits of using composite materials based on glass fibers and their effects.

2. Materials and methods

2.1 Raw materials and provenance

Given the importance of the influence that each characteristic of the components could have on the test results, this part is devoted to the characterization of each component used to make the body of the concrete test (sand, gravel, cement, and water) and its reinforcement in composite material (fiberglass, resin, and hardener). All the raw materials used in our experimental study, as well as their origins, are mentioned in Table 1.

Table 1 – Materials used and their origins.

Materials	Origin		
	Maker	City	Country
Cement 42.5 MPa	ACC Cement Plant	M'sila	Algeria
Sand (0/5)	Oued Baghlia	Boumerdes	Algeria
Gravel 3/8 and 8/15	SCAC Career	Cap Djinet	Algeria
Fiberglass	Johns Manville	Trnava	Slovakia
Resin + hardener	Granitex	Oued Smar	Algeria
Water	ADE	Boumerdes	Algeria

2.1 Used materials

Cement: The cement used is a CPJ grade 42.5 compound cement available from local building supply stores. A control of the physical, chemical and mechanical characteristics was carried out in the laboratory of the Center for Study and Technological Services of the Building Materials Industry CETIM Boumerdès. The results of these tests are reported in Tables 2 to 5.

Table 2 – Mechanical characteristics of cement.

Due in days	$R_{bending}$ (Mpa)	$R_{compression}$ (Mpa)
2 days	5.1	23.7
7 days	6.8	35.8
28 days	7.9	44.9

Table 3 – Physical characteristics of cement.

Features	Withdrawal at	

	Normal consistency	Start of setting	End of take	Cold stability	Hot stability	3 days	7 days	28 days	Mv (absolute)	Fineness of grind (SSB)
Results	29.2	110	220	-	0.5	194	381	600	3.06	4054
Units	%	mn	mn	mm	mm	µm/m	µm/m	µm/m	cm^2/g	cm^2/g

Table 4 – Chemical composition of cement.

Chemical composition	CaO	SiO_2	CaO free	Al_2O_3	K_2O	Na_2O	PF	MgO	SO_3	Fe_2O_3	Ins	Cl^-
Content %	62.78	18.88	0.94	4.65	0.64	0.1	4.6	2.42	2.41	3.2	1.21	0.02
Standard (%)	62 to 67	19 to 25	/	2 to 9	0 to 1.5		/	0 to 3	1 to 5		/	/

Table 5 – Mineralogical composition of cement.

Mineral constituents of clinker	C_3S	C_2S	C_3A	C_4AF	CaO.L	Gypsum
Clinker content (%)	55	21	8	10	1	5
Standard (%)	50 to 60	10 to 20	01 to 15	05 to 10	≤ 02	0 to 5

Sand: The alluvial sand, was used as natural fine aggregates with grain sizes less than 5 mm. The fineness modulus was equal to 2.14. In addition, the absolute density and porosity were estimated at 2.57 g/cm^3 and 40.00 %, respectively. Furthermore, the analysis by sieving or gradation analysis was carried out in accordance with the European standard NF EN 933-1.

Gravel: The gravel is of limestone origin, crushed, and composed of two fractions (3/8) and (8/15). The characteristics of these gravels are presented in Table 6.

Table 6 – Physico-mechanical properties of gravel.

Granular class	Gravel	
Physical property	(3/8)	(8/16)
Apparent density (g/cm^3)	1.363	1.353
Absolute density (g/cm^3)	2.657	2.658
L.A. coefficient (%)	23.56	27.78

The mixing water: The water used is potable tap water. It is suitable for making concrete provided that it meets all the requirements of the NF P 18-303 and EN 1008 standards concerning the concentrations of suspended matter and dissolved salts. Poor-quality water can have adverse effects on concrete, such as carbonation, corrosion of reinforcement, reduction of mechanical strength, acceleration or slowing down of setting time, and the appearance of harmful stains on the surface.

Characterization of the resin: The resin used is the compost material matrix, which was provided by Granitex. This is MEDAPOXY STR brand resin. Its characteristics are given and guaranteed by the supplier and are summarized in Table 7. The supplier also gives a detailed technical data sheet concerning this product, specifying all these characteristics as well as the instructions for use.

Table 7 – The properties of the resin (the polymer matrix).

Features	Results	Units	Photo
Density (iso758)	1.11 ± 0.06	-	

Viscosity (NFT76-102)	11000	MPa.s at 26°C	
Practical duration of use (NFP18 810)	1H16mn	Hours	
Curing time at 20°C and 65%RH			
Ø Excluding poise:	6	Hours	
Ø Hard :	16		
Compressive strength (NA427)	>71	MPa	
Bending strength (NA234)	>26	MPa	
Adherence to concrete	>3	MPa	

Fiberglass: The fiberglass used in the experimental trials of this study from Slovakia. The chemical composition of this product is shown in Table 8.

Table 8 – Chemical characteristics of fiberglass

Constituents		**(%)**
Silica	Sio_2	53-54
Alumina	Al_2O_3	14-14.5
Lime	Cao	20-24
Magnesia	Mg	
Boron oxide	B_2O_3	6.5 - 9
Fluorine	F	0.0.7
Iron oxide	Fe_2O_3	≤ 1
Titanium oxide	TiO_2	
Sodium oxide	Na_2O	≤ 1
Potassium oxide	K_2O	

Figure 2 – Fiberglass used.

2.2 Formulation of concrete

The Dreux Gorisse method is a method used in concrete mix design (Rabehi *et al.*, 2023; Yousfi *et al.*, 2014). This method is utilized to determine the proportions of various ingredients (such as cement, aggregates (gravel and sand), water, and sometimes admixtures) in a concrete mix to achieve desired properties and performance.

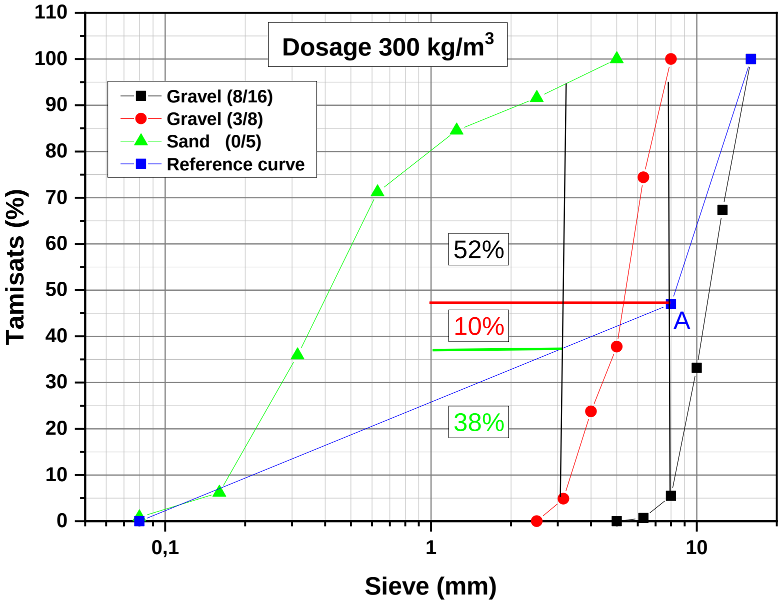

Figure 3 – Granulometric curves of concrete aggregates dosed at (300 kg/m^3).

The concrete composition results are summarized in Table 9.

Table 9 – Dosage for one cubic meter of concrete.

Composition	Dosage	Unit
Cement	300	kg /m^3
Gravel (3/8)	192,381	kg /m^3
Gravel (8/16)	1000.366	kg /m^3
Sand (0/5)	706,304	kg /m^3
Water	155.99	L /m^3
G/S	1.689	-
E/C	0.52	-

2.3 Description of the concrete specimens

The test program was carried out on concrete cylinders of dimensions Ø80 x 160 mm (see Fig.4). Twenty-four (24) cylindrical specimens were tested. The samples were stripped two or three days after pouring and then placed in ambient heat and humidity conditions for 28 days.

The samples from the test program were kept in water in a water tank at a temperature of around 20°C to continue ripening. The surfaces of the specimens intended for bonding the composite are then dried, brushed and well cleaned with a wire brush, which made it possible to obtain a slightly rough and clean concrete surface. The objective of preparing the concrete surface is to remove all traces of oil, grease, laitance, form release product and other dirt in order to obtain a clean and sufficiently rough surface to ensure good adhesion between the concrete test piece and the envelope in composite material.

Figure 4 – Casting and stripping of concrete specimens

Two (02) types of specimens were made from composite plates reinforced with one, two or 3 plies of fiberglass. Five (05) specimens were made for each type, which gives a total of thirty (30) specimens of fiberglass-based composite materials.

Figure 5 – Fiberglass cutting and plates of composite material (fiberglass + resin) after hardening.

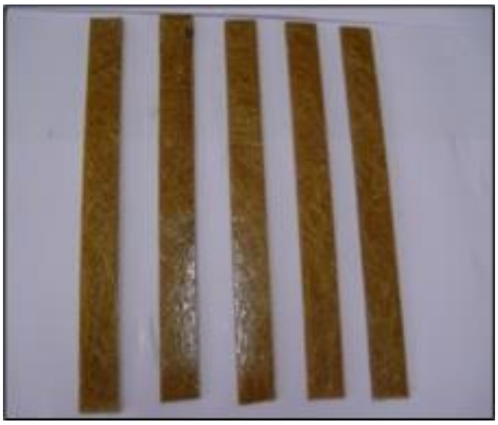

Figure 6 – Cutting of composite material specimens.

2.4 Test program

On the composite material: In order to determine the elastic and mechanical tensile properties of the composite (fiberglass fabric and epoxy resin), simple tensile tests were carried out. Non-woven glass fibers and a MEDAPOXY STR type resin were used for the confinement of the specimens of the main program of this study. Tensile tests were carried out on fiberglass strips 25 mm wide and 250 mm in total length. Simple tensile tests are using the LLYOD Instrument LR30 K machine.

On the concrete specimens: The main test program covered by this study was carried out on crushed concrete specimens without reinforcement with the composite material or after reinforcement with 1 ply, 2 plies or 3 plies of fiberglass. The compression tests were carried out using the ZWICK 250-SN5A universal machine made available to us for carrying out this test program.

The test was carried out namely:

- Static loading with application of the load at a constant rate of increase (0.5 N/mm².s) until rupture of the test body.

The main test program covered by this study was carried out on crushed concrete specimens without reinforcement with the composite material or after reinforcement with 1 ply, 2 plies or 3 plies of fiberglass.

For all the tests on concrete specimens reinforced with FRP or not, the machine settings are as follows:

- Initial load: 10 N.
- Initial load application speed: 10 mm/min.
- Test speed 0.5 (N/mm^2.s).

The stresses are calculated automatically by the control software of the machine used by declaring the dimensions of the specimen before the test (it is the force applied by the machine divided by the concrete surface, without taking into account the rigidity of the confinement " GRP" in the axis of the specimen). The machine provides us with test results in the form of stress-strain curves.

3. Experimental results and discussion

3.1 Results of tensile tests on composite material specimens

The configuration of the machine for carrying out the axial tensile tests was made as follows:

- Distance between extensometer 50 mm. - The test speed 2 mm/min. - Initial load: 10 N.

Tests on flat specimens with 1, 2 and 3 plies of fiberglass: The tensile tests were carried out on five (05) flat specimens made up of one, two and three plies of fiberglass. The stress-strain curves are given by the machine and are presented in Figure 7.

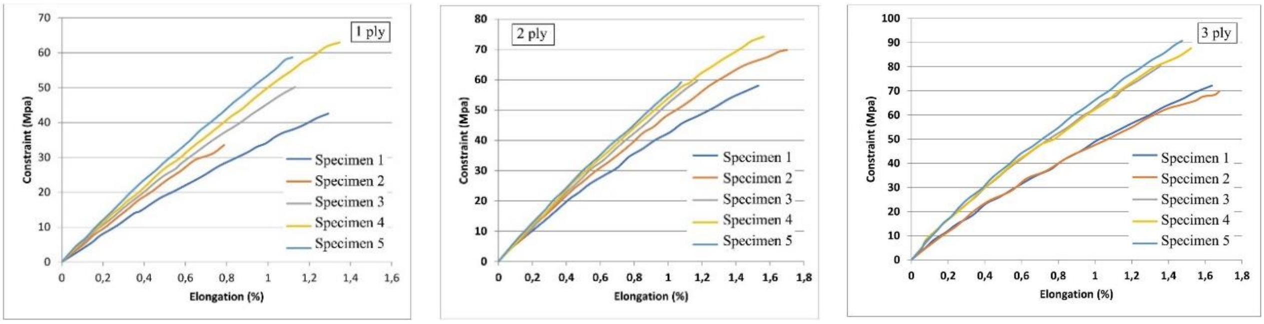

Figure 7 – σ-ε curves for tensile test on 1, 2, and 3 ply FRP flat specimens

Figure 8 shows us the fracture surfaces of specimens made of one, two, and three plies of fiberglass.

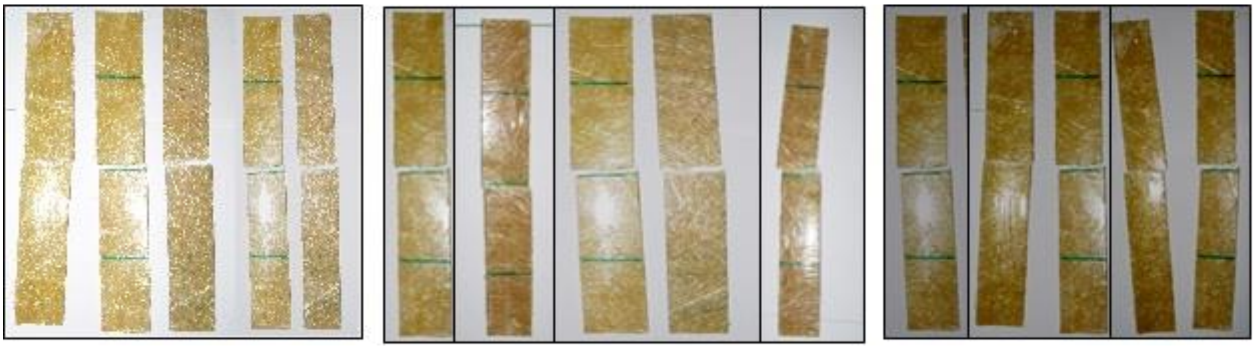

Figure 8 – Fracture surfaces of 1, 2 and 3 ply flat FRPs.

<u>Tests on bent specimens with 1, 2 and 3 plies of fiberglass:</u> The tensile tests were carried out on five (05) curved specimens made up of one (01), two (2) or three (3) plies of fiberglass. The stress-strain curves are given by the machine and are presented in Figures 9.

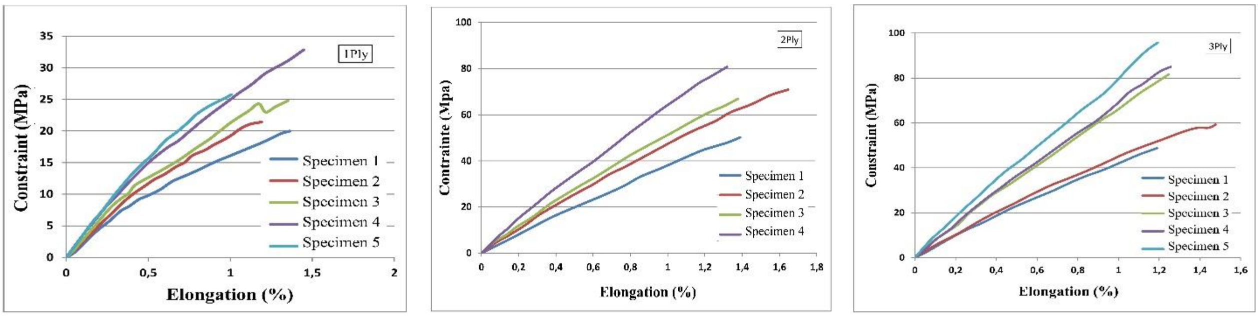

Figure 9 – σ-ε curves for tensile test on 1, 2, and 3 ply FRP bent specimens

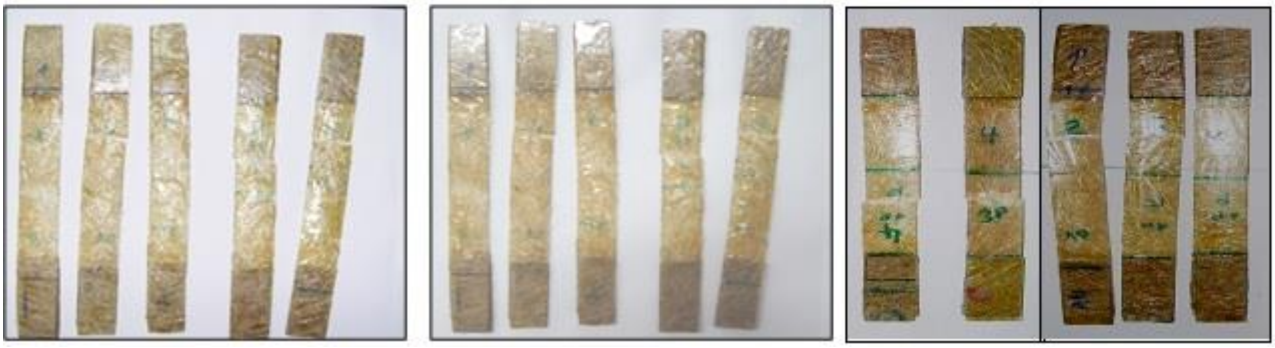

Figure 10 – Fracture surfaces of 1, 2 and 3 ply bent FRPs.

The results of the tensile tests also show a minimal influence of the curvature on the breaking stress values. Except in the case of a bent specimen with a single fiberglass ply for which we obtained a relatively low value.

These tests also showed us the following:

- The fracture surfaces are identical for all the specimens (practically in the middle of the specimen) as shown in Figures 8 and 10.
- Polymers reinforced with fiberglass (FRP) exhibit totally elastic and extremely brittle behavior, hence the absence of the plastic phase.
- Virtually zero ductility of FRP specimens.

- Taking as a reference the maximum stress value of the FRP at 1 ply, we obtain a gain in maximum stress of 29.5% for 2 ply and 61.7% for 3 ply in the case of the flat PRFV and 171.9% and 217.5% in the case of curved PRFV.
- Taking as a reference the maximum deformation value of the PRFV at 1 ply, we obtain a gain in maximum deformation of 24.2% for 2 ply and 53.27% for 3 ply in the case of the flat PRFV and 15.96% and 8.3% in the case of curved PRFV.
- These gains in terms of FRP resistance and deformation are very significant and show the performance that FRPs can have in concrete reinforcement.

3.2 Results of compression tests on concrete specimens

The compressive strength measurements and deformations of the specimens reinforced with one, two, or three plies of fiberglass have been compared to those of the unreinforced specimens. Results of the load tests are outlined below:

<u>Simple compression tests on cylindrical concrete specimens without reinforcement</u> : We carried out compression tests on three (03) concrete specimens without reinforcement. The stress-strain curves given by the machine used are shown in Figure 11 below.

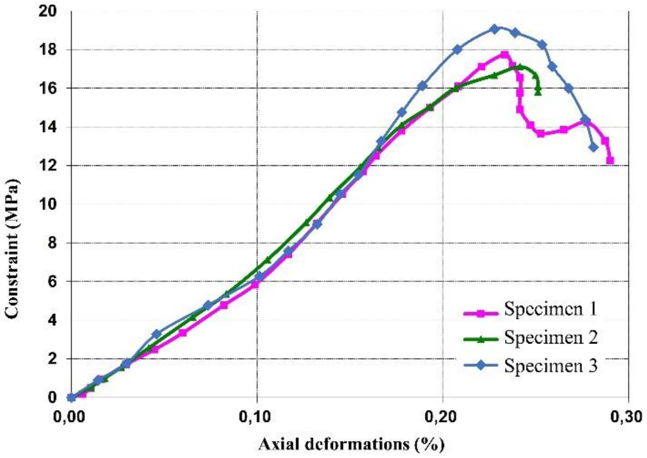

Figure 11 – σ-ε curves for concrete without FRP reinforcement.

Figure 12 – After crushing, concrete specimens without reinforcement.

<u>Concrete reinforced with a 1, 2, and 3-ply fiberglass composite:</u> We carried out compression tests on three (03) concrete specimens reinforced with GRP with one (01) single ply, two (2) and three (03) plies. The stress-strain curves are given by the machine used and are presented in Figure 13, 14 and 15 successively.

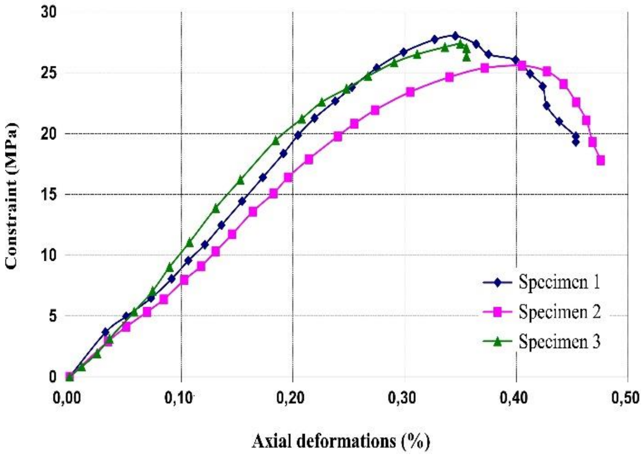

Figure 13 – σ-ε curves for concrete confined by 1-ply FRP.

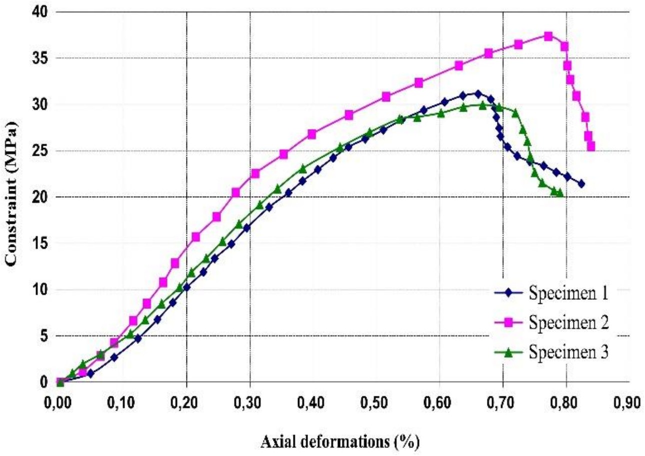

Figure 14 – σ-ε curves for concrete confined by 2-ply FRP.

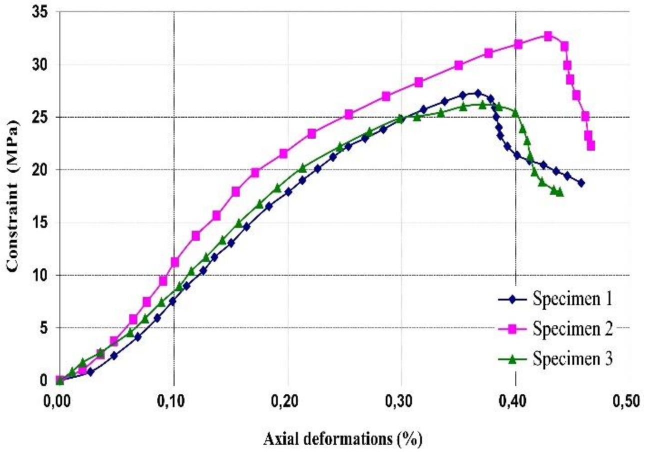

Figure 15 – σ-ε curves for concrete confined by 3-ply FRP.

Figures 16, 17 and 18 show the fracture patterns of the concrete specimens reinforced by GRP with one ply, two and three ply, successively.

Figure 16 – Failure conditions of concrete specimens confined by 1-ply GRP.

Figure 17 – Failure conditions of concrete specimens confined by 2-ply GRP.

Figure 18 – Failure conditions of concrete specimens confined by 3-ply GRP.

Table 10 shows the average values of the maximum stresses and the breaking stresses as well as the average values of the deformations which correspond to these stresses. It also gives the gain values in terms of compressive strength and in terms of deformation taking for the specimens reinforced by FRP (with 1,2 or 3 ply) compared to the unreinforced specimens.

Table 10 – A summary of concrete specimen crushing results.

	Age (Days)	ε (%)	σ max (Mpa)	Gain σ	Gain ε
Concrete alone	35	0.25	18.1	-	-
1ply	35	0.38	26.8	48.1%	54%
2ply	35	0.39	28.8	58.8%	56.8%
3ply	35	0.73	33.0	82.2%	196%

Reading all of these results allows us to perform the following analysis:

1. The curves are characterized for all the specimens (confined by GRP or not) by a linear elastic phase followed by a curvature representing the plastic phase (Li *et al*., 2023).
2. The development phase of concrete microcracking results in a progressive incursion of the curve until the maximum stress σmax corresponding to a certain deformation value ε is reached (Benzerga *et al*., 2023; Castro *et al*., 2013).
3. By imposing slower increases in deformation, we obtain a decreasing curve corresponding to the accentuation of the fracture, that is to say the development of fracture surfaces and generalized cracking (Mazarim *et al*., 2018).

Table 10 gives a comparison of the results obtained depending on the number of fiberglass plies. This table highlights a very significant gain in terms of maximum strength and deformation. Taking as reference the results of crushing the specimens without confinement by FRP, we obtain a gain in compressive strength of 48.1% for reinforcement with 1 ply of glass fiber, 58.8% for 2 ply and 82 .2% for 3 ply. In the same way, we obtain a gain in deformation of 54% for 1 ply, 56.8% for 2 ply and 196% for 3 ply.

5. Conclusions

Typically, stress-strain curves exhibit an initial slope that follows that of unconfined concrete up to an inflection point, followed by a zone of large plastic deformation.

The tests carried out in this study highlight the difficulty of predicting the moment of rupture of the composite envelope.

The ratio of these stresses to the axial compressive strength of unconfined concrete with “PRFV” composite materials makes it possible to evaluate the gains in compressive strength of the different confinement configurations for each series of tests.

The percentage gain in compressive strength (Δσ/ σ0) is a good indication of the effectiveness of the confinement.

The stress gain value can be interpreted as the additional capacity of the specimen to support an axial load compared to a specimen of identical section without confinement.

Concerning axial deformations, in all the specimens tested, external confinement by “PRFV” composite gives a significant gain in axial deformation beyond the elastic phase and therefore a significant improvement in ductility.

The amount of plies used determines how much strength is added to concrete by using a fiberglass-based composite material as reinforcement. Gains for one ply range from 37% to 95% to 150% for three ply. The number of fiberglass plies directly relates to the increase in strength.

A gain proportional to the number of ply was seen for the use of fiberglass in terms of axial deformation. For one ply, the gain is 150%; for two ply, 162.5%; and for three ply, 172.5%. In every instance where the specimens were reinforced, a reduction in radial deformation was seen. This decline is proportional to the number of ply: for fiberglass with 1, 2, and 3 plies, it is 50%, 45%, and 42.5%, respectively.

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