The Influence of the Curing Conditions on the Behavior of Jute Fibers Reinforced Concrete Cylinders

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Abstract

This paper presents an innovative method of reinforcement of concrete based on the use of the Jute fibers composites. These renewable raw bioresource fibers are available at a low cost. Moreover, they can be compared to Glass Fiber-Reinforced Polymer (GFRP) by enhancing the resistance of Jute Fiber-Reinforced Polymer (JFRP), while improving the compatibility between the fiber and the resin. For that purpose, this paper presents an experimental study that evaluates the influence of the curing conditions (time and temperature) on the behavior of JFRP laminates and concrete members strengthened by JFRP. The curing conditions at 30 °C for 2h 30min and at 50 °C for 1 h were the only two parameters studied and determined on the basis of Sikadur 330 properties and preliminary tests. Through the experimental tests, the maximum load capacity and observed failure modes are investigated. The results indicated that the curing at 30 °C for 2h 30min is the optimum curing condition. In addition, a low difference in the maximum load capacity was noted in the case of 50 °C. As to the failure modes, all the specimens cured with additional heat before being left under room conditions, have shown the ductile mode failure, especially in the case of specimens cured at 30 °C during 2h 30min. The analytical model conducted in this paper predicts the elastic modulus depending on temperature. The obtained results and proposed model can be used as input parameters in the analysis and design of externally strengthened members with Jute FRP composites.

Keywords

JFRP composites, epoxy resin, reinforcement, curing conditions, concrete

1 Introduction

The effectiveness of reinforcement of concrete by the synthetic Fiber-Reinforced Polymer (FRP) was approved by several experimental studies [1, 2]. However, these kinds of fibers still have many drawbacks, including high energy consumption during the manufacturing process. Moreover, they are not eco-friendly [3]. This is why strengthening existing structures involves the development of new materials based on natural components [4].

Jute and Flax are one of the most widely used biodegradable fibers in the composite industry. Thanks to their low density and cost. They used as structural strengthening systems for different reinforced concrete (RC) elements such as columns, beams, and slabs [5, 6]. As stated by Hussain and Ali [7], the Jute fibers enhance crack resistance and toughness of concrete. According to Tan et al. [8], the ultimate load of concrete columns has been increased by wrapping with JFRP composites. Alam and Al Riyami [9] showed that the toughness and strength of beams have been improved by the reinforcement using the natural fibers [10, 11]. On the other hand, the maximum load capacity, ductility, and energy absorption have been increased by using the flax fiber-reinforced polymers (FFRP) [12].

While the success of this technique depends, to a large extent, on the charge transfer in the concrete-fiber interface [13–15]. Furthermore, the polymerization conditions affect directly the performance of bonded joints [16] and

more especially the time and temperature which are essential and necessary parameters to trigger the polymerization of epoxy resin and which is frequently underestimated [17]. Since an ambient curing cycle does not achieve the desired performance, many experimental studies have shown that stiffness and strength properties of the concrete increase rapidly due to high curing temperatures. Similar observations confirmed that the minimum curing duration needed for reaching the maximum shear strain was clearly related to the curing temperature [18]. The research conducted by Lapique and Redford [19] has shown that the necessary curing time to reach the maximum tensile strength can be significantly reduced from several hours at room temperature to approximately 30 min at 90 °C. Furthermore, a faster strength evolution was observed at higher temperatures, as the same mechanical properties obtained at 23 °C after 28 days could be attained at 64 °C after only 4 h [20]. Dodiuk and Kenig [21] have observed that the strength achieved after 1 h cured at 60 °C was higher than that obtained after 10–20 days of curing at room temperature. Therefore, it turns out that it is necessary to optimize the time and the temperature; the parameters which can improve the mechanical properties of the composite material, and which could lead to an improvement of the behavior of the reinforced element. And since the effect of curing conditions on the behavior of concrete confined by JFRP composites has never been studied before, so it was necessary to study the behavior of the JFRP composite first and then the JFRP reinforced concrete members. The first section of this paper presents the materials used and the methodology followed. The second section resumes the results obtained from the tensile and compression test in terms of maximum load capacity and failure modes. In the third section, an analytical modeling part was conducted for predicting the elastic modulus in the function of the temperature ranging from 20 °C to 50 °C.

2 Experimental program
2.1 Materials
The used Jute fibers are from Textila Company, Iasi, Romania and the resin used is an epoxy Sikadur 330 delivered by Sika Company from Romania. Table 1 resumes the properties of the Sikadur 330 epoxy resin.

2.2 Preparation of Jute laminates
To characterize the mechanical properties of the composite, the Jute fibers fabric were cut to the dimensions of 25 mm × 250 mm in accordance with ASTM D 3039 [22] (Fig. 1(a)).

The preparation of the composite was performed manually using the wet lay-up process. Each specimen was prepared by applying a layer of epoxy, followed by the Jute fibers fabric and then covered by another layer of epoxy as shown in Fig. 1(a). In order to maintain the nominal dimensions of the specimens, the resin excess was removed by cutting the ends using a universal cutting machine equipped with a diamond disc. All laminates have 1 mm of thickness. The reference specimens were polymerized at room temperature (20 °C). For the specimens whose processes of curing are accelerated and after 1 hour of their preparation; the first group are placed in the oven for 2 h 30 min under 30 °C and for the second group are polymerized for 1 hour at 50 °C. After that, both of them are left at room temperature for 7 days before being tested.

2.3 Preparation of tabs
Tabs increase the total area to which the load applied at both ends, reducing stresses at the end of specimens. Besides, the geometry, tab material, and adhesive must be well selected to minimize stress concentrations near the end of tabs. According to ASTM D 3039 [22], the material used for laminate tabs is sandpaper with a geometry of 25 × 50 mm (Fig. 1).

2.4 Preparation of concrete-JFRP specimens
In the system of reinforcement of the concrete by using the FRP composite, the transition zone is more important when the total porosity of the substrate is higher [23]. Consequently, the concrete surface was prepared to remove the impurities, increase the rate of the pores on the surface, and facilitate the penetration of the resin inside the concrete in order to make a strong bond between the concrete and the composite. The procedure of strengthening the concrete started with concrete surface preparation manually utilizing sandpaper, which led to an increase in surface roughness. Cleaning the lateral surface from dust with high pressure of the air was the second step. Before the application

Table 1 Properties of the Sika-dur 330 epoxy resin

Resin	Density of the mix D (kg/dm³)	Compressive strength $f_{c,a}$ [MPa]	Tensile strength $f_{c,a}$ [MPa]	Modulus of elasticity E [GPa]	Transient glass temperature	Elongation at break εu [%]
Sikadur 330	1.3	30(7 days + 23 °C)	33.8(7 days + 23 °C)	4.5(7 days + 23 °C)	58 °C	0.9

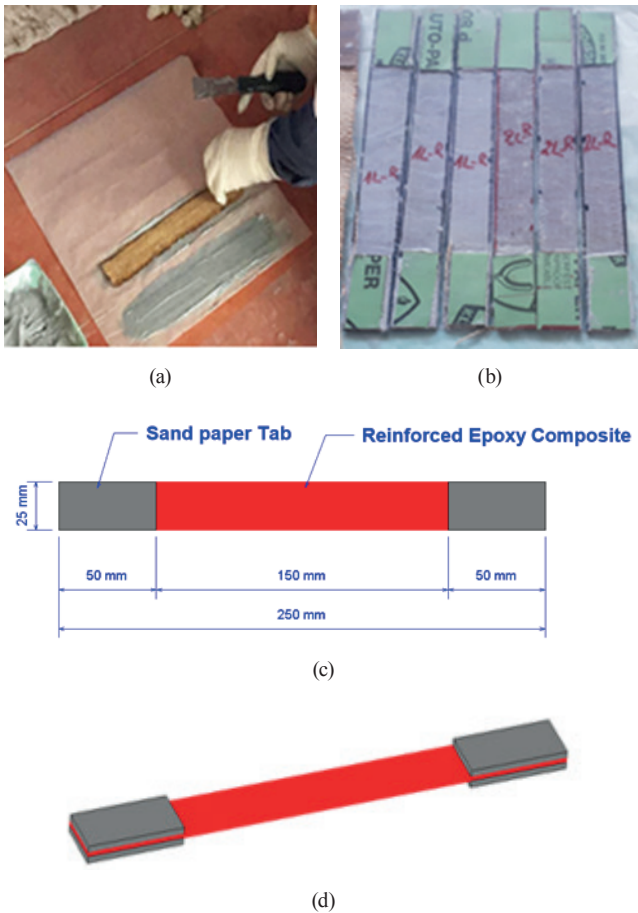(a)   (b)

(c)

(d)

Fig. 1 Details of Jute FRP coupon specimens for tensile testing; (a) Jute composite, (b) JFRP composites coupon specimens, (c) Top view, (d) Side view

of strengthening material, a layer of adhesive was applied firstly to the lateral surface and followed by the Jute fibers fabric, and then covered by another layer of epoxy. And to ensure a good bond between the concrete-JFRP and to avoid any entrapped air bubbles at the epoxy/fabric or epoxy/concrete interface, the Jute fibers fabrics were applied with constant pressure with a roller. The adhesive Sikadur 330 used is a bi-component adhesive, consisting of a resin and a hardener agent with a mixing ratio of 4:1. The components were mixed in a clean and transparent container for 3 min at circular speeds of 400–600 RPM.

2.5 Curing step

This study tested 18 cylindrical specimens of 100 mm diameter and 200 mm high, including 3 unconfined and 15 JFRP-confined cylinders specimens which are divided into 5 groups. The first group of concrete-JFRP members which designed as reference specimens are left at room temperature (20 °C) for 7days before being tested. For the specimens whose curing process is accelerated, were left

under ambient conditions for an hour after the application of the strengthening system (Fig. 2(a)) and before being placed in the oven. Those specimens are divided into four groups (as summarized in Table 2). Specimens which cured at 30 °C for 2 h 30 min were left at room temperature for 3 days. Specimens cured at 30 °C for 2 h 30 min, then kept for 7 days at room temperature. Specimens cured at 50 °C for 1h and left at room temperature for 3 days. Specimens cured at 50 °C for 1 h and kept at room temperature for 7 days. The oven used in this experimental part is a universal MEMMERT 100–800 oven (Fig. 2(b)) that has a maximum temperature of 200 °C. The temperature inside the oven was controlled by using a digital system as shown in (Fig. 2(c)).

2.6 Mechanical testing
2.6.1 Tensile test

In order to characterize the mechanical properties of the Jute-FRP composite, the laminates were tested by applying a uniaxial load across both ends of the specimens,
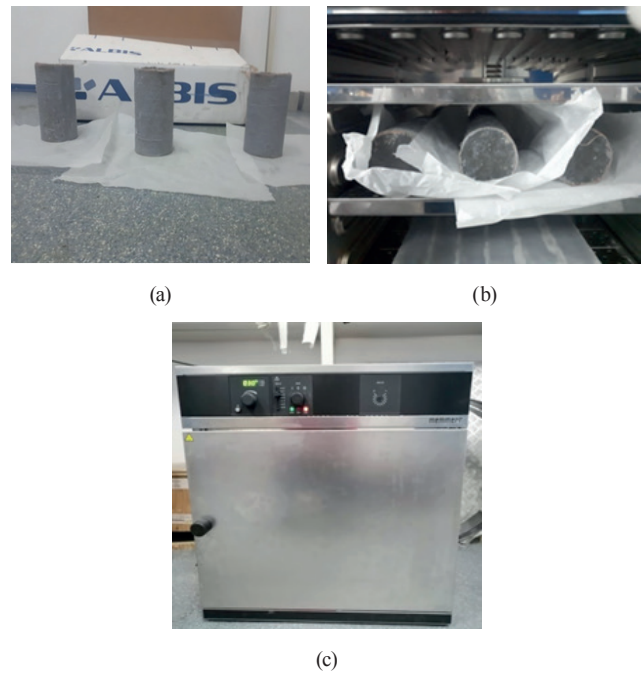

(a)   (b)

(c)

Fig. 2 (a) Specimens before accelerated curing process, (b) Specimens placed in the oven, (c) Oven used

Table 2 Curing conditions specimens

Group	Details
1st group	20 degree C, 7 days
2snd group	30 degree C, 2 h 30 min for 3 days
3rd group	30 degree C, 2 h 30 min for 7 days
4th group	50 degree C, 1 h for 3 days
5th group	50 degree C, 1 h for 7 days

using suitable jaws of attachment to the WAW-600 E universal testing machine. Both ends of the laminates are fitted with tabs. The tensile test was carried out in the composite materials laboratory in Iasi which all specimens are prepared and tested according to ASTM D3039 [22] guidelines. Laminates are pulled in tension at a rate of 2 mm/min. The load-displacement of each specimen is recorded using data acquisition Maxtest software which is connected to the lower and upper load cells.

2.6.2 Compression test

All the specimens cured at room temperature, 30 °C or 50 °C, and tested after 3 or 7 days come under compression testing using the Universal Testing Machine WAW-600 E with 4KN/s applied loading speed (Fig. 3). All the specimens are prepared and tested following the NF EN 12390-3 [24] standard. On other hand, in the aim to avoid eccentricity generation during axial load application, two circular discs laid on both sides of the concrete specimens, one on the upside and the second one on the bottom. The results are obtained using the data acquisition system Maxtest software.

3 Results and discussions
3.1 Failure Mode of JFRP Laminates

The straight fracture was observed perpendicular to the axial stress direction (as shown in Fig. 4), and the failure occurred in a brittle manner. The ruptures produced in areas far from the extremities of laminates, which explain the advantages of using tabs that reduce stresses in the composite at the end of specimens. All laminates cured at room temperature, 30 °C or 50 °C displayed failure modes per ASTM D 3039 [22] (Paragraph 11.9) which are lateral failures and can be referred to as an L.G.M (Lateral Gage middle) failures (Fig. 4). Changing the temperature from 30 °C to 50 °C, the failure modes have appeared the same as observed at room temperature (20 °C).

3.2 Interpretation of Load-Displacement behavior of JFRP Laminates

The laminates have been evaluated parallel to the axis of application of the tensile force. All the curves obtained have linear elastic behavior until breakage. The maximum load capacity was 1.33 KN, corresponding to a 3.85 mm
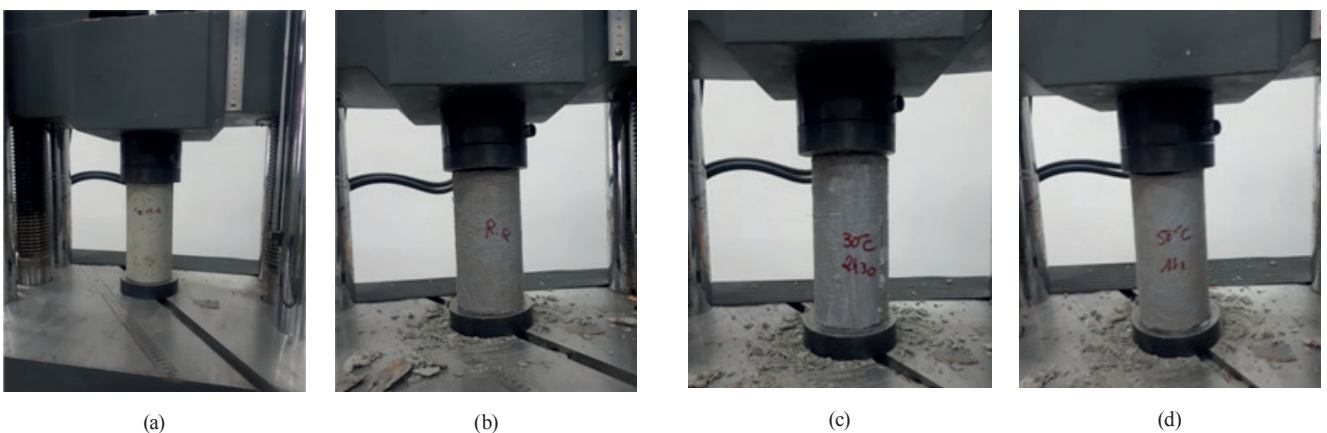

(a)   (b)   (c)   (d)

Fig. 3 (a) Unreinforced specimens, (b) Reinforced specimens, (c) Specimens cured at 30 °C for 2 h 30, (d) Specimens cured at 50 °C for 1 h

(a)   (b)   (c)   (d)   (e)
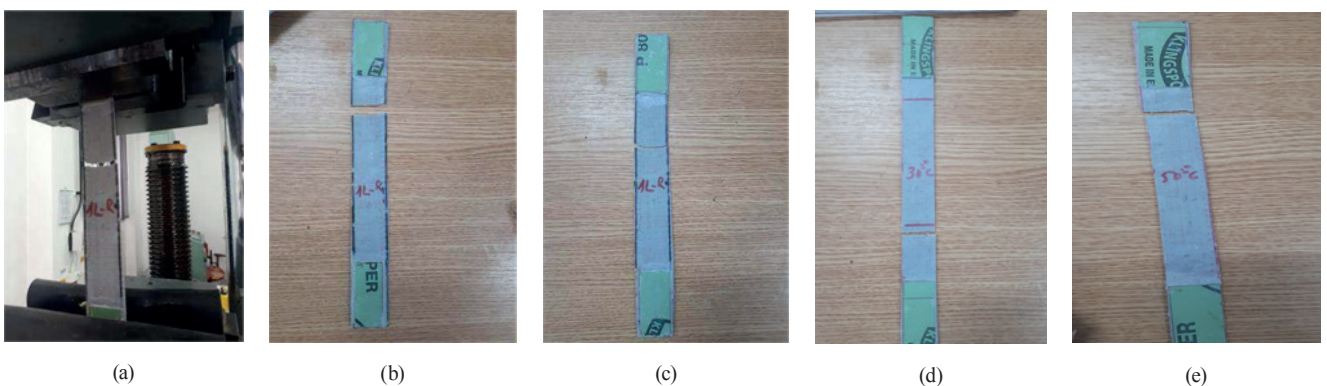
Fig. 4 Failure modes of JFRP laminates; (a) JFRP laminate during the tensile test, (b) Failure mode of JFRP lamniate cured under room temperature (1), (c) Failure mode of JFRP lamniate cured under room temperature (2), (d) Failure mode of JFRP lamniate cured under 30 °C for 2 h 30 min, (e) Failure mode of JFRP lamniate cured under 50 °C for 1h

displacement for specimens cured at 30 °C for 2 h 30 min and tested after 7 days. And 1.14KN for specimens cured at 50 °C and tested after 7 days. The less value was noted in the case of specimens cured at room temperature with 0.9 KN and 2.6 mm of displacement (Fig. 5).

By analyzing the achieved results, it can be concluded that increasing the temperature from 20 to 30 °C (just for 2 h 30 min) allows increasing the maximum load by 47%. And increasing the curing temperature from 20 °C to 50 °C just for1h allows increasing the load value by 26.7%. This shows the positive effect of accelerating the curing process while relying on additional heat. As far as the curing time is concerned, 2 h 30 min for the case of 30 °C was more than enough to reach a superior value of maximum load capacity as compared to specimens cured at the ambient conditions (7 days under 20 °C). Contrary, in the case of 1 h for the 50 °C, it was perhaps necessary to increase the curing acceleration time by a few more minutes.

3.3 Mechanical properties of JFRP-Laminates
Following the Eqs. (1), (2), and (3) the mechanical properties are summarized in Table 3.

Ultimate tensile strength [MPa]:

$$\sigma = \frac{F}{S} . \tag{1}$$

Elongation at failure [%]:

$$\varepsilon = 100 \times \frac{\Delta l}{l} . \tag{2}$$

Elasticity modulus at failure [GP]:

$$E = \frac{\sigma}{\varepsilon} . \tag{3}$$

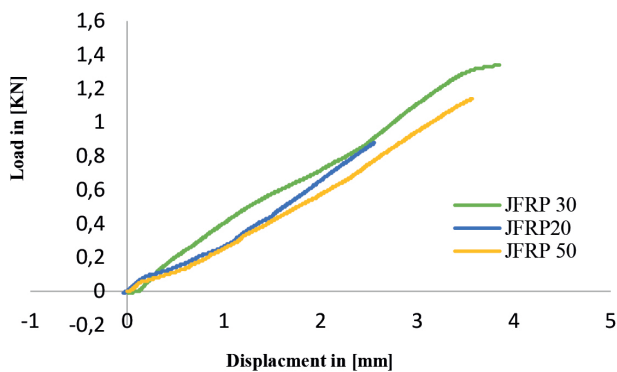As shown in Table 3, the maximum values of tensile strength have been increased in the case of 30 °C and 50 °C, compared to laminates cured at room temperature (specimens cured at 20 °C). This increase was also noted by Mhanna et al. [25] who explained that the mechanical properties of epoxy improve at higher temperatures below Tg due to increased production of crosslinkages which led to the rapid initiate chemical reactions.

On the other hand, the laminates hardened at 50 °C were noted a less value of elasticity modulus compared to specimens cured at 30 °C.

3.4 Interpretation of load-displacement behavior of concrete JFRP-composites
Analyzing the load-displacement curves as shown in Fig. 6, Fig. 7 and Table 4, all specimens have a non-linear behavior up to failure. Specimens cured at 30 °C and crushed after 3 or 7 days as well as those cured at 50 °C and crushed after 7 days, have noted the maximum compressive force with maximum displacement. For specimens cured at 30 °C for 2 h 30 min and crushed after 3 or 7 days, showed similar behavior and similar maximum load capacity with a low difference of the displacement value.

Ambient cured specimens (C-JFRP-R) have shown a lower displacement and load capacity than the specimens cured at 30 °C crushed after 3 or 7 days (C-JFRP-30-3, C-JFRP-30-7) and those cured at 50 °C and disrupted after 3 days or 7 days (C-JFRP-50-3, C-JFRP-50-7).

Table 3 Properties of the JFRP laminate

	Cured at 20 °C	Cured at 30 °C	Cured at 50 °C
Ultimate tensile strength [MPa]	36	53.2	45.6
Elasticity modulus at failure [GPa]	3.46	3.45	3.28
Elongation at failure [%]	1.04	1.54	1.39

Fig. 5 Load-Displacement curves of laminates cured at room temperature 20 °C, at 30 °C for 2 h 30 min and at 50 °C for 1 h

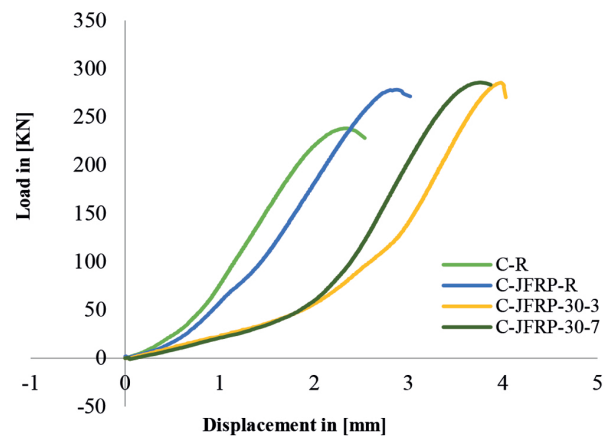**Fig. 6** Load-displacement curves of compressive tests on unreinforced and reinforced concrete cylinders
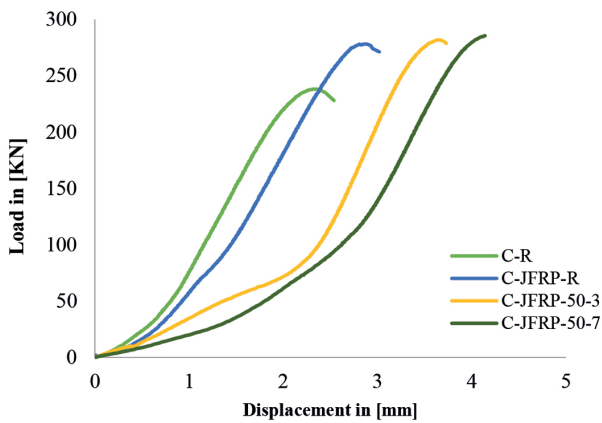
Fig. 7 Load-displacement curves of compressive tests on unreinforced and reinforced concrete cylinders

Table 4 Specimen details, average maximum load and displacement

Code	Signification	Average maximumm load capacity [KN]	Displacement [mm]
C-R	Plain concrete (reference)	238.2	2.356
C-JFRP-R	JFRP reinforced concrete cured at room temperature	278.2	2.88
C-JFRP-30-3	JFRP reinforced concrete cured at 30 °C during 2 h 30 and tested after 3 days	285.6	4.07
C-JFRP-30-7	JFRP reinforced concrete cured at 30 °C during 2 h 30 and tested after 7 days	285.8	3.76
C-JFRP-50-3	JFRP reinforced concrete cured at 50°C during 1h and tested after 3 days	282	3.649
C-JFRP-50-7	JFRP reinforced concrete cured at 50 °C during 1 h and tested after 7 days	285.6	4.12

On the other hand, the specimens cured at 50 °C and crushed after 3 days (C-JFRP-50-3) exhibited similar behavior to specimens cured at room temperature (C-JFRP-R) with a small variation in maximum load.

3.5 Interpretation of maximum load capacity of concrete JFRP-composites

As shown in Fig. 8, reinforcing the concrete members with the Jute fibers fabric increased the maximum load capacity by 16.8% compared to unreinforced specimens. The case
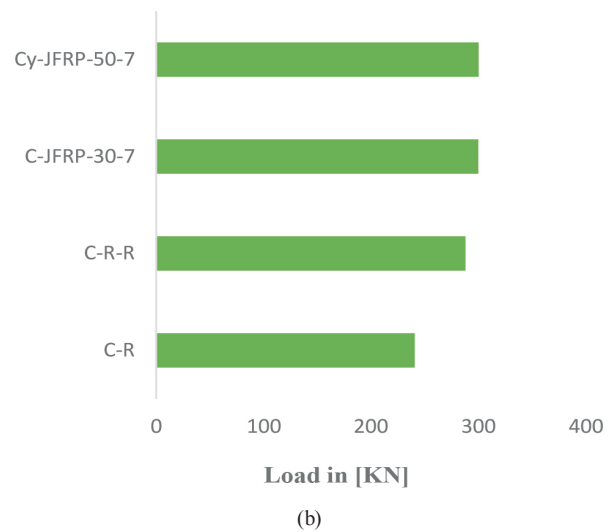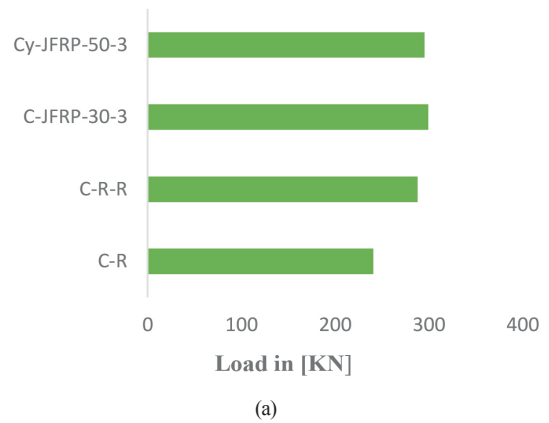

(a)

(b)

Fig. 8 Comparison of average maximum load capacity; (a) Specimens tested after 3 days of the curing process, (b) Specimens tested after 7 days of the curing process

of specimens cured under 30 °C for 2 h 30 min and crushed after 3 days, displayed a 19.9% of increase in the maximum load capacity compared to unreinforced samples and 2.66% compared to reinforced specimens cured under room temperature. Specimens cured under 30 °C for 2 h 30 min and crushed after 7 days showed an increase of 2.8% and 20% compared to reinforced specimens cured under room temperature and unreinforced members, respectively. Moreover, after 3 days of curing, the crushing of the reinforced members, cured at 50 °C for 1 hour showed an increase in the breaking load of 1.37% compared to reinforced specimens (cured under room temperature) and 18.39% compared to unreinforced specimens. The members crushed after 7 days displayed an increase of 2.66% and 19.9% compared to reinforced patterns cured at room temperature and unreinforced specimens, severally.

Following the results obtained, all specimens cured with additional heat (30 °C for 2 h 30 min and 50 °C for 1 h) showed a higher load capacity compared to specimens

cured at room temperature. Czaderski et al. [26] confirmed that all samples exsiccated for 30 minutes at 90 °C (whether tested minutes after the heating process or after 2 days) fail at higher forces than those for reference specimens cured at room temperature. The study conducted by Al-Tamimi et al. [18] confirmed the improvement of bonds in CFRP systems when exposed to an elevated temperature due to polymer crosslinking and the creation of complex interactions. On the other hand, the results obtained from the tensile test demonstrate that adhesion between fiber and matrix is improved which can explain more the improvement of the behavior of concrete reinforced by JFRP composites.

Besides, it turns out a very low difference variation in the maximum load capacity in the case of specimens cured below 30 °C (crushed either after 3 days or after 7 hardening days), and specimens cured below 50 °C and crushed after 7 curing days. The fact that the specimens reached the maximum resistance only after 3 days of curing which is the same resistance found in the case of the specimens crushed after 7 days, confirms that 2 h 30 min with 30 °C of temperature were the optimal conditions that led to a correct crosslinking.

On contrary, the least value of the ultimate load was noted in the case of specimens cured at 50 °C for 1 h and crushed after 3 days; this means that these conditions were not enough to reach an important crosslinking. Furthermore, the results show that increasing the temperature from 30 °C to 50 °C did not improve the maximum load capacity.

On the other hand, increasing of the curing time gave values almost similar to those found in specimens cured at 30 °C for 2 h 30 min and crushed after 3 days.

As a conclusion, the observed improvement confirms that the curing process of some adhesive systems at room temperature involves additional heat to raise the temperature of specimens above the glass transition temperature (Tg). By heating the specimens above the Tg value, reactive groups become mobile again, and the curing can reach high levels of crosslinking. The extent of the curing reaction influences the final structure of the adhesive network, which changes the overall properties of the cured epoxy network [27]. The crosslinking density depends on the processing conditions and especially on the polymerization temperature. Hence, each reaction site becomes a crosslinking node; the compactness of nodes will condition the internal cohesion of the joint. A dense network shows reduced molecular mobility of chains and high rigidity. On the other hand, a low crosslinking density

leads to a loose matrix, in which chains slide relative to each other. The network cohesion will be weak and the joint will poorly transmit the forces between the two assembled parts.

3.6 Failure modes of concrete cylinders reinforced with JFRP-composites

The following figures present the failure modes of all unconfined (Fig. 9) and confined cylinder specimens (Fig. 10–12). All the specimens cured with additional heat
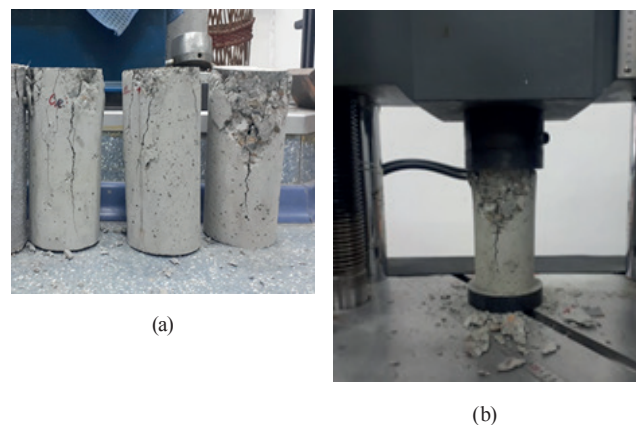

(a)

(b)

Fig. 9 Unconfined cylinders specimens; (a) Specimens after the test, (b) Specimens during the compression test

Fig. 10 Confined cylinder specimens cured at room temperature

Fig. 11 Confined cylinder specimens cured at 30 °C for 2 h 30

Fig. 12 Confined cylinder specimens cured at 50 °C for 1 h

before being left under ambient conditions have shown a ductile mode failure, especially in the case of specimens cured at 30 °C for 2 h 30 min. It was observed two longitudinal ruptures and one other discontinuous rupture from the bottom of the specimens to the middle with the apparition

of some cracks from the top (Fig. 11). This kind of rupture where the rupture in the FRP laminate originates from the top surface and continues throughout the bottom in a single line is called continuous laminate rupture.

The specimens cured at 50 °C showed more than three longitudinal failures, which explains that the strength of the adhesive layer had not developed as a whole during this duration and under this temperature (Fig. 12).

On the other hand, the specimens cured under room temperature have shown a high number of cracks with continuous and discontinuous longitudinal rupture.

In conclusion, the difference noticed was in the number of cracks that appeared on the specimens. More precisely, in the case of the unreinforced specimens, a very high number of cracks were observed. Generally, they are concentrated at the upper part with the appearance of other cracks spread along the length of the specimens. On the other hand, in the case of the concrete-JFRP specimens, the difference was also noticed at the level of the detachment of the composite from the concrete, this mode of failure was very remarkable only in the case of specimens that were cured under ambient conditions. This detachment explains that the bond created between the JFRP and concrete was not strong enough (Fig. 10).

4 Modeling of Elastic Moduls of JFRP laminates cured at elevated temperature

As indicated previously, increasing the curing temperature enhanced the strength of the JFRP laminates. On the other hand, the elastic modulus has noted a decrease of 5.48% in the case of 50 °C compared to specimens of reference. Using existing analytical models that simulate the modulus of elasticity of FRP materials as a function of temperature, this study predicts the experimental results.

In the literature, the general model proposed by Gibson et al. [28] as indicated in Eq. (4) predicted the variation of the Elastic Modulus of FRP materials in terms of temperature:

$$P(T) = R^n \left[\frac{P_u + P_R}{2} - \frac{P_u - P_R}{2} \left\{ \tanh(k_m (T - T')) \right\} \right], \quad (4)$$

with:

$P(T)$ is the elastic modulus at a specified temperature T, P_u and P_R which represents the elastic modulus of the material at room temperature and the relaxed modulus of the material, respectively. k_m and T' are variables determined by fitting the experimental data of the laminate. All those coefficients based on a regression analysis. R^n is a power law factor based on the residual resin content.

The use of composite materials based on carbon fibers, basalt or a combination of carbon and basalt or polyethylene terephthalate generates different behaviors, which give rise to new models to predict the mechanical properties as in terms of temperature variation, including those of Mhanna et al. [25], Hawileh et al. [29], and Yu and Kodur [30]. In the study initiated by the group of Mhana et al. [25], the PET-FRP laminates have displayed a nonlinear behavior that opposes the linear response of the CFRP and BFRP materials used by Hawileh et al. [29], Yu and Kodur [30].

This work focuses on a comparison of the experimental results with the following models developed to predict the modulus of elasticity based on Gisbon's equation.

Mhanna et al. [25] have developed three models because the stress-strain response has exhibited a nonlinear behavior which led to dividing curves into three phases with three moduli (E_1, E_2 and E_3):

$$E_1(T) = 0.57 - 0.425 \tanh\left[(0.032(T - 76.52))\right], \quad (5)$$

$$E_2(T) = 0.572 - 0.428 \tanh\left[(0.024(T - 69.65))\right], \quad (6)$$

$$E_3(T) = 0.727 - 0.273 \tanh\left[(0.018(T - 72.43))\right]. \quad (7)$$

Hawileh's et al. models [29]:

The following models predict the elastic modulus of carbon (C), basalt (B) and carbon-basalt (BC) at elevated temperatures:

$$E_c(T) = 0.55 - 0.455 \tanh\left[(0.014(T - 60.27))\right], \quad (8)$$

$$E_B(T) = 0.86 - 0.140 \tanh\left[(0.035(T - 163.24))\right], \quad (9)$$

$$E_{BC}(T) = 0.705 - 0.295 \tanh\left[(0.091(T - 196.34))\right]. \quad (10)$$

Yu and Kodur [30] predicted the elastic modulus of CFRP strip:

$$E(T) = 0.51 - 0.49 \tanh\left[(0.0035(T - 340))\right]. \quad (11)$$

And proposed for CFRP bars the following model:

$$E(T) = 0.51 - 0.49 \tanh\left[(0.0033(T - 320))\right]. \quad (12)$$

4.1 Comparison of experimental results with analytical models

Fig. 13 compares experimental data to predicted results using published models in the literature. As shown in Fig. 13, the model (1) (Eq. (5)) of Mhanna et al. [25] gave results close to the experimental results. On the other
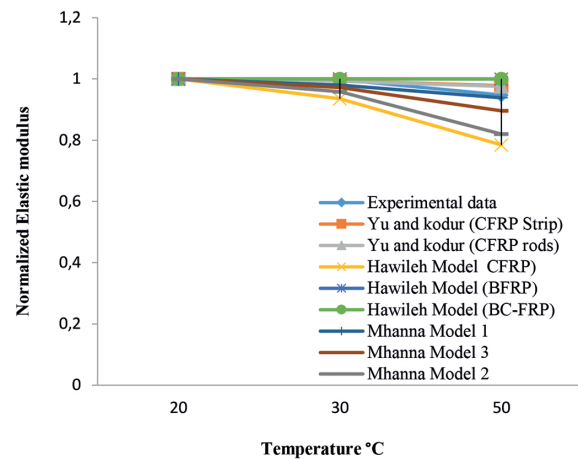

Fig. 13 Comparison between experimental data and predicted results using published models in the literature

hand, the second model (Eq. (6)) and third model (Eq. (7)) of Mhanna et al. [25] as well as the models of Hawileh et al. [29], Yu and Kodur [30], did not predict the experimental results. For the two curves given by the Yu and Kodur [30] models, whether for the case of CFRP or CFRP strips, rods divide into two parts. For the fraction between 20–30 °C, the values displayed are lower than the experimental values. On the other hand, from 30-50 °C, the fractions are higher than the experimental results. The same in the case of both models of Hawileh et al. [29] (BFRP) and (BC-FRP) Eq. (9) and Eq.(10), gave higher values compared to experimental results. The model of Hawileh et al. [29] (CFRP) Eq. (8) gave lower fractions compared to the probing values. The three models of Mhanna et al. [25], showed lower amounts compared to the probing values. The difference in fractions in the case of Hawileh et al. [29] resides in the difference between the types of materials in use, precisely in the case of basalt-based composites or the combination of basalt and carbon. The difference noted in the case of Yu and Kodur [30] can be explained by the use of CFRP rods or strips whose behavior and capacity differ in a complementary way compared to the same JFRP parameters. The work of Mhanna et al. [25] and Hawileh et al. [29] concluded that, for models based on strips and rods conducted on Near Surface Mounted (NSM), strips and rebars cannot predict the results of laminates prepared by wet lay-up. This conclusion applies to model (2) (Eq (6)), and model (3) (Eq. (7)) of Mhanna et al. [25] as well. On the other hand, a small difference appeared in the case of the model (1) of Mhanna et al. [25] (Eq. (5)), explained by the fact that this model only represents the first part of the response, which gave values close to the experimental values.

4.2 Proposed model

To find a model that predicts the experimental results, a square regression analysis performed to obtain the coefficients (km, T') based on Gibson et al. [28] equation. To achieve a minimum square error between the experimental data and the empirical model, a Microsoft Excel "solver" function was used. Table 4 resumes the calculated coefficients of the elastic modulus for the JFRP laminates.

This paper proposes the following model Eq. (13) for predicting the elastic modulus of JFRP at elevated temperatures:

$$E(T) = 0.880 - 0.546 \tanh\left[(0.082(T - 65.90)\right]. \qquad (13)$$

As a result and from Fig. 14 that shows a comparison between experimental and predicted results, it is clear that a close correlation exists between predicted and measured results of modulus of elasticity of JFRP laminates in terms of variation of curing temperature.

As shown in Table 5, the predicted elastic modulus values using the model developed in this study had a small Mean Absolute Percent Error (MAPE) of 0.02%, and the correlation coefficient (R) equal to 0.999985.

In general, if the correlation (R) is between 0.2–0.5, a moderately weak correlation applies. If it is between 0.8 and 1.0, a strong relationship applies. If it is between 0.5 and 0.8, a slight correlation applies.

The results show clearly the close correlation between predicted and experimental results. So, the developed model can be used to predict the elastic modulus of JFRP Laminates at elevated temperatures. It can be used as input parameters in computer simulation to evaluate the behavior of concrete strengthened by the JFRP.
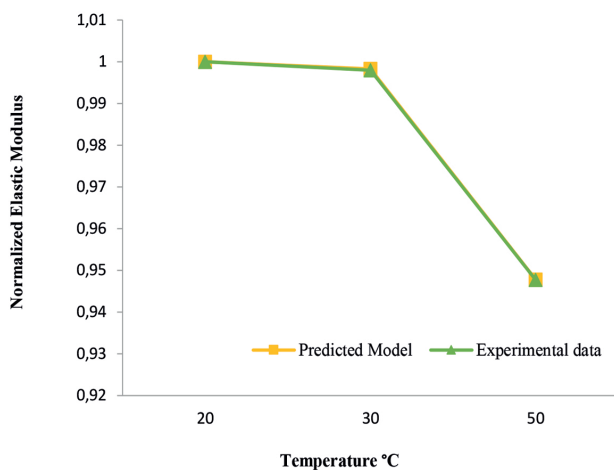

Fig. 14 Comparison of measured and predicted elastic modulus results for JFRP laminates using the proposed model

5 Conclusions

Results of this investigation reveal the following observations and conclusions:

1. The reinforcement of concrete elements with Jute fiber fabrics increased the maximum load capacity by 19.6% compared to unreinforced specimens.
2. In the case of elements cured at 30 °C for 2 h 30 min and crushed after 3 days, an increase in the maximum breaking load of 24.4% was noted compared to unreinforced specimens. And 4% was noted compared to reinforced specimens cured at room temperature.
3. The results have shown in the case of elements cured under 30 °C for 2 h 30 min and crushed after 7 days, an increase of 4.14% compared to reinforced specimens cured at room temperature and 20.6% compared to unreinforced elements.
4. The reinforced of concrete elements by JFRP cured at 50 °C during 1 hour and left for 3 days of curing (under room conditions) have shown an increase in the breaking load of 2.54% and 22.6% compared to reinforced specimens and unreinforced specimens, severally.
5. In the case of reinforced elements cured under 50 °C for 1 hour and left for 7 days under ambient conditions, an increase was noted of 4.3% compared to reinforced specimens cured at room temperature and 24.7% compared to unreinforced specimens.
6. All the specimens cured with additional heat before being left under ambient conditions have shown the ductile mode of failure, clearly, observed in the case of specimens cured at 30 °C and 50 °C.
7. A very high number of cracks was noted in the case of the unreinforced specimens. On the other hand, in the case of reference concrete members reinforced by JFRP (cured under ambient conditions), a detachment of the composite from the concrete was observed. Which demonstrated that the bond created between the JFRP and concrete was not strong enough.

Table 5 Derived coefficients based on Gisbon et al model [28] for elastic modulus of JFRP laminates

Coefficient	Laminate JFRP
P_u	1
P_R	0.76
K_m	0.082
T'	65.90
MAPE(%)	0.02
R	0.99985

8. The adhesion between the fiber and matrix is improved, which led to an improvement of the behavior of concrete reinforced by JFRP composite. All the results obtained from the tensile test were used to further demonstrate the contribution of curing conditions on the behavior of concrete confined by JFRP composites.

9. The developed model can be used to predict the elastic modulus of the JFRP Laminates at elevated temperature and as input parameters in computer simulation to evaluate the behavior of concrete strengthened by JFRP.

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