



PBPC
ISSN 2674-9432



Qualis A3
CAPES 2021-2024



DOI - Crossref

Latindex

Indexado no
Google Acadêmico

INFLUENCE OF GRAPHENE ADDITION IN EPOXY RESIN APPLIED TO CARBON FIBER STRUCTURAL REINFORCEMENT OF CONCRETE BEAMS

Taila Brandes Abrahão¹; Virgínia Turatti Coladetti²; Arthur Medeiros³, Juliana Regina Kloss⁴; Wellington Mazer⁵



<https://doi.org/10.36557/2674-9432.2026v5n2p5-24>

Artigo recebido em 1 de Fevereiro e publicado em 1 de Abril de 2026

ARTIGO ORIGINAL

ABSTRACT

Structural reinforcement plays a key role in preserving and adapting structures that are nearing the end of their useful life, that were built according to obsolete standards, or that need to be adapted for new uses beyond their original capacities. The use of carbon fiber reinforced polymers (CFRP) stands out for this function, as it has good mechanical and corrosion resistance, low density, and minimal alteration in the geometry of the reinforced element. However, premature detachment of CFRP, resulting from adhesive characteristics such as brittle fracture mode and low fracture toughness, can compromise the structural stability of the system. In connection with this, recent research has focused on improving polymer matrices by incorporating nanomaterials, such as graphene, which provides greater toughness and mechanical strength to the composite when properly dispersed. Based on this, the objective of this study was to evaluate the influence of adding graphene to epoxy resin applied to carbon fiber structural reinforcements in concrete beams. The composite was produced by incorporating graphene into the epoxy resin, using a torque rheometer for dispersion; its functional groups, thermal, and mechanical properties were analyzed by *Fourier transform infrared spectroscopy (FTIR)*, thermogravimetric analysis (TG/DTA), and tensile test. The beams were subjected to a four-point bending test, in which data were obtained on the stress at the appearance of the first crack, breaking stress, and evaluation of the failure mode of the samples. The experimental data showed that the compositions with graphene had a greater deformation capacity before failure. However, the cracking and rupture stresses of the beams reinforced with the epoxy/graphene composite and with the pure resin were statistically equal. As this result is linked to the failure mode, there remains the possibility that graphene contributes to improving structural reinforcement, especially in increasing toughness - the ability to absorb energy before rupture.

Keywords: Adhesive; CFRP; polymer matrix; nanocomposites; toughness.

RESUMO

O reforço estrutural desempenha um papel fundamental na preservação e adaptação de estruturas que se aproximam do fim de sua vida útil, que foram construídas segundo normas obsoletas ou que necessitam de adaptação para novas aplicações que ultrapassem suas capacidades originais. O uso de polímeros reforçados com fibra de carbono (PRFC) destaca-se por essa função, apresentando boa resistência mecânica e à corrosão, baixa densidade e mínima alteração na geometria do elemento reforçado. Contudo, o desprendimento prematuro do PRFC, resultante de características adesivas como modo de fratura frágil e baixa tenacidade à fratura, pode comprometer a estabilidade estrutural do sistema. Nesse contexto, pesquisas recentes têm se concentrado na melhoria de matrizes poliméricas pela incorporação de nanomateriais, como o grafeno, que proporciona maior tenacidade e resistência mecânica ao compósito quando adequadamente disperso. Com base nisso, o objetivo deste estudo foi avaliar a influência da adição de grafeno à resina epóxi aplicada a reforços estruturais de fibra de carbono em vigas de concreto. O compósito foi produzido pela incorporação de grafeno à resina epóxi, utilizando um reômetro de torque para dispersão. As propriedades funcionais, térmicas e mecânicas do compósito foram analisadas por espectroscopia de infravermelho com transformada de Fourier (FTIR), análise termogravimétrica (TG/DTA) e ensaio de tração. As vigas foram submetidas a um ensaio de flexão em quatro pontos, no qual foram obtidos dados sobre a tensão no aparecimento da primeira fissura, a tensão de ruptura e a avaliação do modo de falha das amostras. Os dados experimentais mostraram que as composições com grafeno apresentaram maior capacidade de deformação antes da ruptura. No entanto, as tensões de fissuração e ruptura das vigas reforçadas com o compósito epóxi/grafeno e com a resina pura foram estatisticamente iguais. Como esse resultado está relacionado ao modo de falha, permanece a possibilidade de que o grafeno contribua para a melhoria do reforço estrutural, especialmente no aumento da tenacidade – a capacidade de absorver energia antes da ruptura.

Palavras-chave: Adesivos, PRFC, matriz polimérica, nanocompósito, resistência.

Instituição afiliada – 1 - Master student, Federal Technological University of Paraná, PPGE/DACOC/UTFPR, Curitiba, Paraná, Brazil, e-mail: taila@alunos.utfpr.edu.br, ORCID 0009-0008-2247-9119
2 - Graduation student, Federal Technological University of Paraná, DACOC/UTFPR, Curitiba, Paraná, Brazil, e-mail: virginiacoladetti@alunos.utfpr.edu.br, ORCID 0009-0004-6324-670X
3 - PhD Professor, Federal University Technological of Paraná, PPGE/DACOC/UTFPR, Curitiba, Paraná, Brazil, e-mail: arthurmedeiros@utfpr.edu.br, ORCID 0000-0003-2061-0108
4 - PhD Professor, Federal University Technological of Paraná, PPGE/DAQBI/UTFPR, Curitiba, Paraná, Brazil, e-mail: julianakloss@utfpr.edu.br, ORCID 0000-0002-3632-6219
5 - PhD Professor, Federal University Technological of Paraná, PPGE/DACOC/UTFPR, Curitiba, Paraná, Brazil, e-mail: wmazer@utfpr.edu.br, ORCID 0000-0002-9941-999X, Corresponding author.

Autor correspondente: *Wellington Mazer*

This work is licensed under a [Creative Commons Attribution 4.0](https://creativecommons.org/licenses/by/4.0/)



International License.

1 INTRODUCTION

Reinforced concrete structures, widely used in civil construction, can suffer performance loss over time due to factors such as design and construction errors, functional changes, inadequate maintenance, natural and environmental disasters, overloads, system modifications, and others (Heiza et al, 2014). Given this, when the structural capacity is not adequate for its use, the application of structural reinforcement techniques becomes an efficient alternative to restore the performance of these structures (Irshidat, Al-Saleh, 2016; Reis, 2001).

For structural reinforcement to achieve the desired performance, the structure must be investigated in its entirety, and the reinforcement method must be chosen to increase the resistant capacity while minimizing the need for maintenance and repair (Silva, 2022). Technical, economic, and socio-environmental aspects must also be considered when choosing the best method, which may vary from case to case (Reis, 2001).

The most used techniques for structural reinforcement include the addition of reinforcement, increasing the cross-section, external prestressing, applying metal plates, and using composite materials (Silva, 2022). However, solutions associated with reinforced concrete lead to an increase in the existing cross-section, an increase in the structure's own weight, and metal reinforcements generate the need for frequent maintenance (Panigrahi, 2013).

Thus, carbon fiber reinforced polymers (CFRP) emerge as an alternative due to their high rigidity, mechanical strength, resistance to temperature and corrosion, ease of handling and installation, high strength-to-weight ratio, and minimizing changes in geometry (Florek et al, 2021; Irshidat, Al-Saleh, 2017).

CFRPs are marketed in the form of blankets, composed of interwoven fibers forming a flexible fabric that can be adapted to different surfaces, and sheets, formed by unidirectional layers of fiber and resin, generally providing greater tensile strength (Balaguru et al, 2008). The application can be done by different methods, such as EBR (Externally Bonded Reinforcement), which can be used for both mats and sheets, and NSM (Near Surface Mounted), a method exclusive to sheets (Wierzbicki, 2021).

In addition to the application method and design quality parameters, fiber orientation, matrix type, composite stiffness, elastic modulus, material interface adhesion, and Poisson's ratio of the CFRP also influence the performance of reinforcement with this technique (Balaguru et al, 2008; Irshidat et al, 2015; Wang et al, 2014). Failures in these aspects can lead to delamination or detachment, limiting the overall performance of the reinforcement (Truong et al, 2020; Yan et al, 2023).

Both carbon fiber and resin have limitations for optimal interface functioning. The

surface of carbon fiber has low chemical reactivity and reduces wettability (Florek et al, 2021). The resin has low toughness and a brittle fracture mode. As a result, there is a need for improvements in the interface, which can be achieved by enhancing the properties of adhesive materials through matrix modification (Irshidat, Al-Husban, 2022; Reale Batista, Drzal, 2018; Wu et al, 2020).

An alternative to improving the performance of resins is the introduction of additives to modify the properties of polymers to obtain more tenacious matrices without compromising strength (Huang et al, 2017; Schuster, 2017; Xiong et al, 2021). Currently, the use of nanomaterials is growing and can improve the adhesion between the carbon fiber/epoxy resin composite and concrete (substrate). In this sense, graphene, due to its large surface area ($2630 \text{ m}^2 \cdot \text{g}^{-1}$), Young's modulus (1.0 TPa), and tensile strength (130 GPa), shows promise as a nanomaterial for this type of application (Guest et al, 2023; Huang et al, 2017; Schuster, 2017; Da Luz et al, 2020; Chen et al, 2023).

Thus, the present research aims to evaluate the influence of adding graphene to epoxy resin applied to carbon fiber structural reinforcements in reinforced concrete beams subjected to tensile stress in bending. To this end, the structural, thermal, and mechanical properties of the epoxy resin/graphene composite were analyzed, and the performance of structural reinforcements in concrete beams with and without the incorporation of graphene in the epoxy resin was compared.

2 MATERIALS AND METHODS

Materials

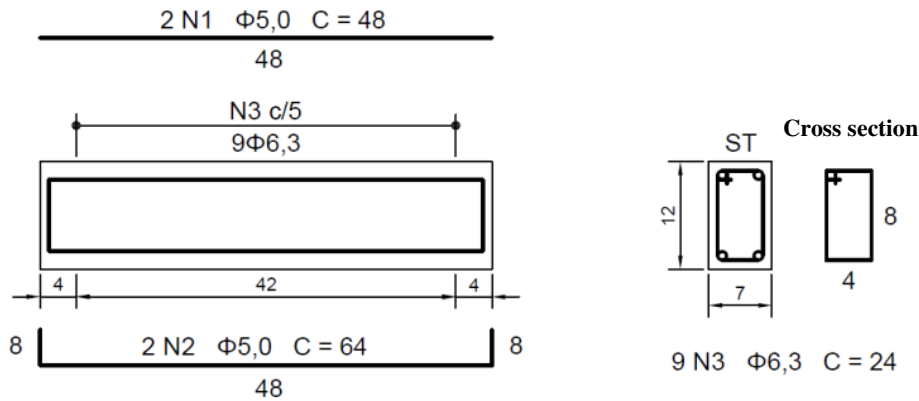
For the development of this research, the following materials were used, with properties obtained from the respective technical datasheets: epoxy-based structural adhesive, two-component, thixotropic, with a density of 1.33 g/cm^3 , in a ratio of 3 (resin): 1 (hardener), adhesion of 14 MPa in 1 day, and deformation modulus of 4.7 GPa; 2D heterostructure graphene with up to 50 layers, density of 0.4 g/cm^3 , decomposition temperature of $450 \text{ }^\circ\text{C}$, and molecular mass equal to 12.01 g/mol ; unidirectional carbon fiber blanket, with elasticity modulus of 240 kN/mm^2 , tensile strength of $4,300 \text{ N/mm}^2$, weight in the main direction of 300 g/m^2 , deformation at break of 1.8 %, and thickness of 0.168 mm; and reinforced concrete, made with 25.0 MPa ready-mix concrete, maximum aggregate size of 9.5 mm and slump of $19.0 \pm 3.0 \text{ cm}$, and CA-50 steel.

Designing and detailing of beams and reinforcements

The beams were dimensioned according to the guidelines of NBR 6118 (ABNT, 2023) to support a load of 40 kN without reinforcement, but without considering the weighting coefficients, aiming at a reliable comparison with the experimental results.

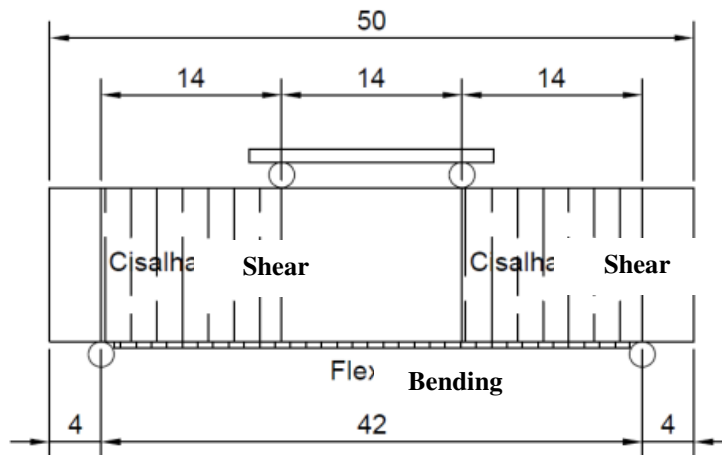
In addition, as the objective of this study is to evaluate the bending behavior of the beam, changes were made to the dimensioning to facilitate bending failure, resulting in the detailing shown in Figure 1.

Figure 1 – Beam schematic layout and detailing.



The reinforcements were calculated using the method of standard 440.2R-17 (ACI, 2008), resulting in a layer of carbon fiber blanket glued to the underside for flexural reinforcement and, for shear, two layers of fiber across the entire length of non-zero shear stress, glued in a U-shape to the top and sides, so as not to create an anchor for flexural reinforcement (Figure 2).

Figure 2 – CFRP structural reinforcement: Schematic drawing.



Legenda Caption:

- Rolete Suport roller
- ▭ Manta CFRP

Production of reinforced beams

Beam specimens were cast at a reduced scale, with dimensions of 7.0 × 12.0 × 50.0 cm, limited by the capacity of the testing equipment used for failure. A total of twelve (12) beams were produced. The formwork and reinforcement cages were assembled in advance, and the concrete was supplied by a local ready-mix provider in accordance with the previously specified parameters. In addition to the beams, six cylindrical specimens (10.0 × 20.0 cm) were cast to determine the compressive strength, following the procedures outlined in NBR 5738 (ABNT, 2015).

The epoxy/graphene composite was produced in a quantity of 650 grams, sufficient to perform the material tests and reinforce six beams in bending. The dispersion of graphene in the resin was performed using the Thermo Scientific Haake Reomix 600 torque rheometer, operating at 80 rpm for 10 minutes at room temperature. The proportion of graphene used was 0.25% (w/w) graphene/component A of the epoxy adhesive, established based on a review of the literature (Sheshmani et al, 2013; Hsieh et al, 2011; Raffie et al, 2009; Wang et al, 2023).

The beams were then separated into two groups for the application of CFRP reinforcement: six pieces were reinforced using conventional epoxy adhesive (reference), and the other six using the epoxy resin composite with graphene (Table 1).

Table 1 – Groups of reinforced concrete beams and structural reinforcements applied

Group	Description	Reinforcement		Number of samples
		Bending	Shear	
A	Reference beams: reinforced with conventional CFRP bonded using epoxy resin	Conventional resin	Conventional resin	6
B	Experimental beams: reinforced with CFRP bonded using epoxy/graphene composite resin	Epoxy/graphene composite	Conventional resin	6

The reinforcement was applied in the following steps: preparation of the beam surface, with leveling, rounding of corners, and removal of dust. Next, a layer of primer was applied, the resin components were mixed in a 3:1 ratio (epoxy resin or epoxy/graphene composite: hardener), and a layer approximately 1 mm thick was applied along the length of the beam.

The blanket, cut to 7.0 × 40.0 cm, was placed over the resin layer with the aid of a grooved metal roller, pressing it against the substrate to remove air bubbles. After this process, another layer of epoxy resin was applied to saturate the blanket, forming a protective layer.

The shear reinforcement was performed a week later, to allow the epoxy to cure completely. The same procedure was followed as for the flexural reinforcement, with a few exceptions: an extra layer of blanket was placed, and only conventional epoxy resin was used. The beams then remained in the laboratory at room temperature for another seven days to allow the resin to be cured. Finally, the sides of the beams were painted white to make it easier to see any cracks.

Analyzes

Before applying the epoxy/graphene composite to the beams, the material was analyzed using the following tests: *Fourier* transform infrared spectroscopy (FTIR) to identify chemical groups; TGA/DTA (thermogravimetric analysis) to analyze stability and thermal transitions; and tensile strength to compare the mechanical behavior of

pure epoxy resin with the epoxy/graphene composite.

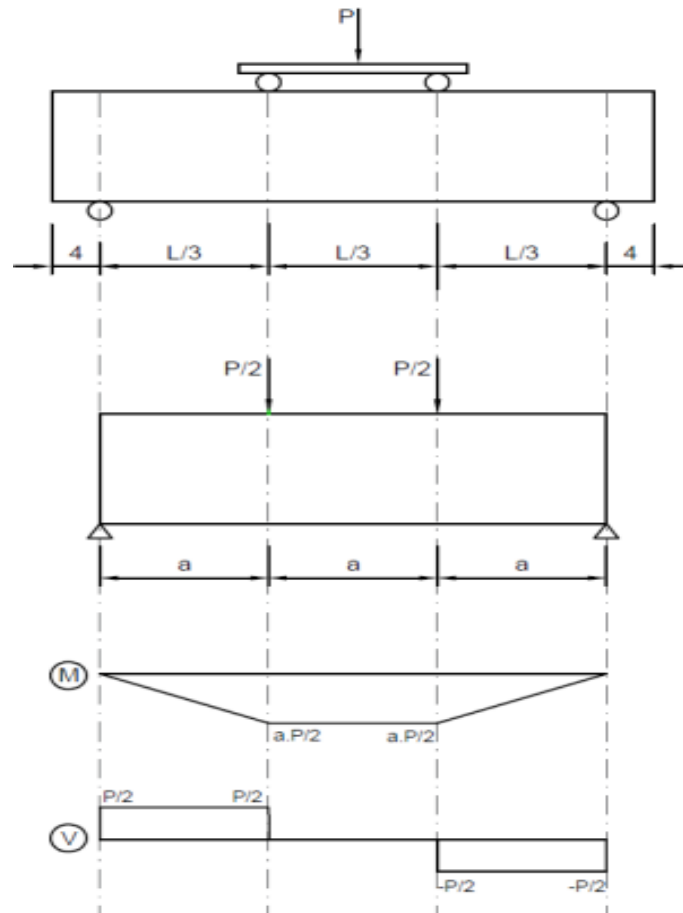
The spectra in the infrared region were obtained using a PerkinElmer Spectrum Two spectrophotometer, with a resolution of 4 cm^{-1} , 32 scans, and a wavelength range of 4000 to 650 cm^{-1} , using the attenuated total reflectance (ATR) technique.

TGA/DTA analyses were performed on a Shimadzu DTG-60H simultaneous TGA/DTA measuring instrument (max. $1,500\text{ }^{\circ}\text{C}$), where samples with an approximate mass of 9.0 to 18.0 mg were placed in open alumina supports at a heating rate of $20\text{ }^{\circ}\text{C}/\text{min}$, ranging from 25 to $600\text{ }^{\circ}\text{C}$, under a nitrogen atmosphere with a flow rate of $50\text{ mL}/\text{min}$.

For the tensile test, six type I specimens (CP) of epoxy/graphene resin and six reference CPs were produced and tested in a Shimadzu AG-I machine, using a 10 kN load cell and a test speed of $5\text{ mm}/\text{min}$ at room temperature. During the test, the modulus of elasticity (E), tensile strength (σ), and total deformation (ϵ) were obtained. The compressive strength of the concrete was verified in accordance with NBR 5739 (ABNT, 2018) by testing the six cylindrical specimens ($10.0 \times 20.0\text{ cm}$), at 64 days, the date coinciding with the rupture of the beams.

The performance of the reinforcements was evaluated using a four-point bending test, which consists of applying two-point loads of equal intensity to the beams, positioned to generate a central region subjected to pure bending (Figure 3), in accordance with standards C78/C78M (ASTM, 2021) and NBR 12142 (ABNT, 2010). The test allowed the collection of information on the tensile strength in bending, the load at which the first crack appeared, the mode of rupture, and the delamination load of the samples.

Figure 3 - Four-point bending test diagram on reinforced concrete beam.



The force intensities were measured using a PCE100C ESP NO: 11687 NS 390 electro-hydraulic press with an Emic IDC3 digital indicator from the manufacturer EMIC, with a nominal capacity of 1000 kN. The flexural tensile strength values were determined using Equation 1.

$$\sigma = \frac{P \times l}{b_w \times h^2} \quad (\text{Eq. 1})$$

Where P is the breaking load, l is the length of the beam, b_w is the width, and h is the height of the beam.

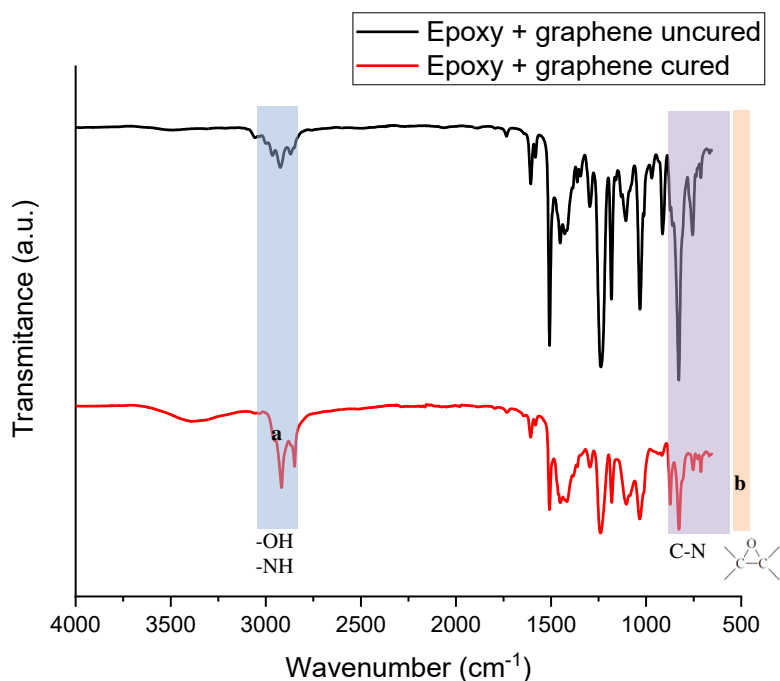
The data obtained were subjected to statistical treatment, in which *Student's* t-test was applied to verify the existence of significant differences at a 95 % confidence level between the means of the two groups analyzed.

3 RESULTS AND e DISCUSSION

Analysis of the epoxy/graphene composite

Through *Fourier* transform infrared spectroscopy (FTIR) testing, it was possible to identify the chemical functions present in the epoxy/graphene composite, both cured and uncured (Figure 4).

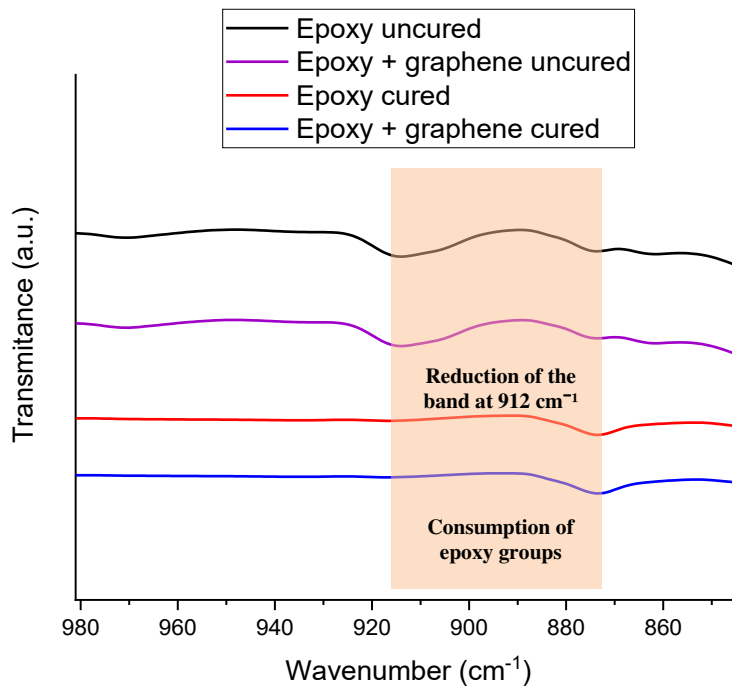
Figure 4 – Spectrum obtained in the infrared region with *Fourier* transform of the cured and uncured epoxy/graphene composite



Spectrum analysis enabled the identification of the epoxy curing reaction. The appearance of a broad band around 3382 cm⁻¹ is attributed to O–H stretching vibrations, indicating the formation of hydroxyl groups during the curing process. Additionally, the presence of N–H stretching bands confirms the involvement of amine hardeners in the cross-linking reaction. The significant reduction of the absorption band at 912 cm⁻¹, characteristic of the epoxy ring, indicates the progressive consumption of epoxy functional groups, thus confirming the occurrence of the curing reaction and the formation of a cross-linked polymer network (Barbosa, 2007; Ribeiro, 2015; Yuste-Sanches, 2019).

When comparing the spectrum of conventional epoxy resin and graphene-containing epoxy resin (Figure 5), in both states, it was not possible to identify the interference of the nanomaterial in the cross-linking reaction. This can be explained by the percentage of nanoparticles incorporated into the composite or by the limitation of technical sensitivity (Abdi et al, 2022; Wazalwar et al, 2021).

Figure 5 – Comparison of the spectra obtained in the infrared region with the *Fourier* transform of pure epoxy and cured and uncured epoxy/graphene composite



Note: The spectrum is enlarged in the region of epoxy group consumption.

Thermogravimetric analysis, performed on both cured samples (after mixing with the hardener and curing time) and uncured samples (only component A of the epoxy resin or component A + graphene), showed onset temperatures (T_{onset}) and end of degradation temperatures (T_{endset}), and the temperature of maximum mass loss rate (T_{max}) is indicated in Table 1.

Table 1 – Thermogravimetric analysis results: onset, maximum degradation rate, and end temperatures for uncured and cured epoxy resin and epoxy/graphene composite

Sample	T_{onset} (°C)	T_{max} (°C)	T_{endset} (°C)
Uncured epoxy resin	263 _a	354 _c	415 _e
Uncured composite	255 _a	350 _c	409 _e
Cured epoxy resin	339 _b	371 _d	410 _f
Cured composite	340 _b	371 _d	408 _f

Note: Equal letters indicate statistically equal results at a 95% confidence level.

When analyzing the results, it was possible to see that there was no difference between the temperatures of the pure epoxy resin (reference) and the cured epoxy/graphene composite. This similarity was also observed by Silva *et al.* (2013), who also did not observe significant differences when incorporating graphene oxide into the epoxy matrix. For the uncured samples, the composite presented T_{onset} 3.04 % lower than the pure resin. The reduction in thermal stability can be attributed to the increase in free volume, which may also act as a barrier to the diffusion of volatiles.

To analyze the results of the tensile strength test on the cured epoxy resin and epoxy/graphene composite samples, the average data, after exclusion of spurious data, for the tensile strength and modulus of elasticity of the test elements are

presented in Table 2.

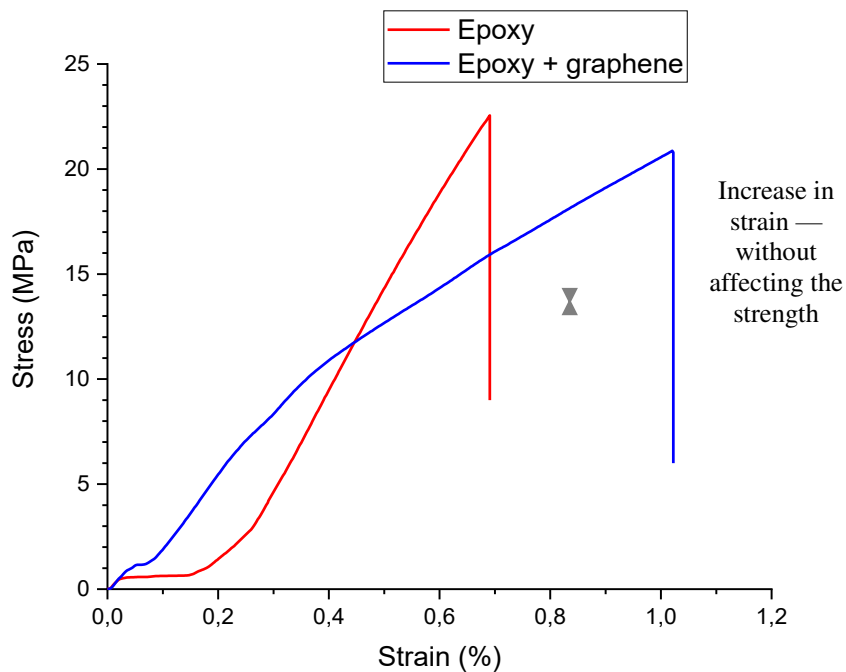
Table 2 – Mechanical properties of pure epoxy resin and epoxy/graphene composite produced in the torque rheometer

Sample	Tensile strength	Standard deviation	Modulus of elasticity	Standard deviation	Deformation at break
Group	MPa	MPa	MPa	MPa	%
Epoxy resin (reference)	23.9 _a	1.4	18.8 _c	2.7	0.7
Epoxy/graphene composite	23.7 _a	1.9	15.0 _d	1.8	1.0

Note: Equal letters indicate statistically equal results at a 95% confidence level.

A numerical difference of only 0.2 MPa in tensile strength and 3.8 MPa in modulus of elasticity was observed between conventional epoxy resin and epoxy/graphene composite. The composite showed a 20.21% reduction in elastic modulus, indicating greater ductility without affecting strength (Figure 7), a result like that of Silva *et al.* (2013).

Figure 7 – Comparison of the composite and reference by tensile strength: stress x strain



The reduction in the modulus of elasticity when adding graphene to the epoxy resin, observed in this study, may be related to the formation of agglomerates that can act as points of stress concentration and crack nucleation. This leads to the possibility that the optimum degree of dispersion has not been achieved.

In the literature, there are cases in which the incorporation of nanomaterials increased the elastic modulus of the composite and cases in which it decreased: the increase in polymer entanglement density increases Young's modulus, but the formation of agglomerates decreases the elastic modulus (Abdi et al, 2022; Silva et al, 2013;

Lavoratti et al, 2018).

Another important property analyzed was toughness, which was determined by calculating the area under the stress–strain curves. The results indicated that the epoxy/graphene composite increased the toughness of the epoxy matrix by 107.69% without compromising its mechanical strength. This improvement is attributed to the incorporation of graphene, which enabled the adhesive to absorb and dissipate energy under applied loading, thereby reducing the risk of brittle fracture, cracking, and delamination of the carbon fiber sheet (Florek et al, 2021; Sharma et al, 2022; De Cicco et al, 2017; Kinloch, Young, 1995; Rafiee et al, 2020).

Analysis of the application of the epoxy/graphene composite in beams

Cylindrical test specimens (10.0 x 20.0 cm) were tested to determine the strength of the concrete used in the beams, which were tested on the same day as the beams, measuring their actual strength on the date of the beam test (Table 3). The results showed an average of 33.8 MPa, with a standard deviation of 0.6 MPa.

Table 3 – Compressive strength of the concrete used in the beams

Sample number	Breaking load	Breaking stress
Index	kg	MPa
1	27500.0	34.3
2	27740.0	34.6
3	26,920.0	33.6
4	26,880.0	33.6
5	26,580.0	33.2
6	26,640.0	33.3
Average	27,043.3	33.8
Standard deviation	471.8	0.6

To analyze the performance of structural reinforcements with carbon fiber mats, applied with adhesive with and without graphene to the beams, four-point bending strength tests were performed. In this test, stress corresponding to the onset of cracks, the breaking stress, and the failure mode of the beams were obtained (Table 4).

Table 4 – Stresses acting on and failure mode of reinforced beams

Group	Number of samples	First crack stress	Standard deviation	Failure stress	Standard deviation	Mode of rupture
	un	MPa	MPa	MPa	MPa	
A	6	16.0 _a	1.5	27.1 _b	1.0	Delamination of the concrete layer

B	5	14.5 _a	2.4	24.9 _b	2.6	Delamination of the concrete layer
---	---	-------------------	-----	-------------------	-----	------------------------------------

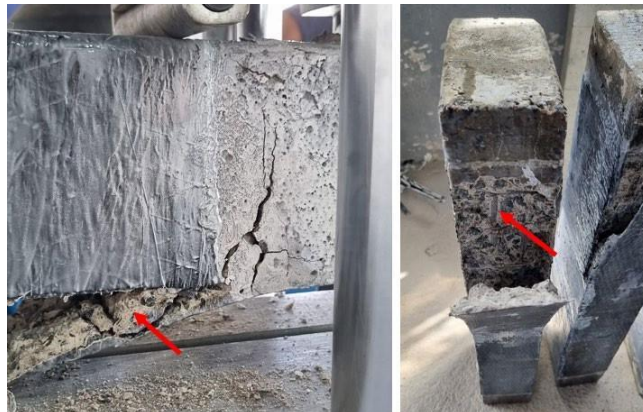
Note: Group A: Reference beams (conventional reinforcement) and Group B: Beams with flexural reinforcement bonded with epoxy/graphene composite.

Note: Equal letters indicate statistically equal results at a 95% confidence level.

The test indicated stresses at the onset of the first crack and at the failure of the beams reinforced with pure epoxy resin, which were numerically higher than those reinforced with composite material. However, statistical analysis showed that these stresses were equal at a 95% confidence level.

The lack of statistical difference in the flexural tensile strength of the reinforced beams can be attributed to the mode of failure, since the delamination of the concrete layer occurred, and not the detachment of the carbon fiber mat. This shows that the failure was not related to the adhesion or interface between the substrate and reinforcement, but rather between the reinforcement and the concrete. The delamination of the concrete layer was confirmed by the existence of concrete fragments adhered to the carbon fiber, emphasizing that the failure occurred in the plane of the reinforcement, as can be seen in Figure 4.

Figure 4 - Failure mode: delamination.



The failure mode, due to delamination of the concrete layer, is related to the poor quality of the steel-concrete interface in the reinforced concrete beams, as well as the loss of adhesion before the plasticization of the steel caused by shear stresses. Other factors, such as the difference between the elasticity modules of concrete (32.6 GPa) and steel (210 GPa), as well as the reduction in the size of the reinforcement, cover, and anchorage, aiming at the proportions of the reduction in the beam dimensions (7.0 x 12.0 x 50.0 cm), corroborated the concentration of stress in this region.

Another factor that could be associated with the lack of statistical difference in tensile strength is that, in relation to mechanical strength, the incorporation of graphene did not provide improvements. The effect of graphene was observed only in the toughness of the composite, which had a lower modulus of elasticity than pure resin, indicating greater deformation capacity and stress absorption.

The improvement resulting from the increased toughness of the resin was not observed in the beams, since the crack initiation stress of the composite reinforcement was statistically equal to that of the reference beams. The first crack appeared at a stress of approximately 15 MPa in the central region subjected to pure bending. With the increase in load, new cracks formed near the supports and, as they widened, delamination occurred between the steel and the concrete, initially near one end and gradually spreading to the other.

This failure mechanism can be attributed to insufficient anchorage length, resulting in higher shear stress at the ends of the carbon fiber blanket, as also observed by Irshidat et al. (2016). Comparing the results of this study with those of similar research, Irshidat et al. (2016) also found no changes in the crack initiation stress and recorded an increase of only 5% in the ultimate load. However, Irshidat and Al-Husban (2022) and Irshidat and Al-Saleh (2017) observed a delay in the appearance of the first crack, and Irshidat and Al-Saleh (2017) reported a 24% increase in the ultimate load.

In general, there is no consensus on the degree of improvement provided by the incorporation of nanomaterials in the epoxy resin used in the adhesion of carbon fiber reinforcements in reinforced concrete elements. This variability in results is associated with factors such as nanoparticle morphology, dispersion quality, interfacial interactions, and reinforcement stiffness, highlighting the complexity of the subject.

However, as the rupture occurred without full utilization of the reinforcement system, there remains the possibility that graphene contributes to the improvement of structural reinforcement, especially in increasing the energy absorption capacity before rupture.

4 CONCLUSIONS

In summary, this research aimed to evaluate the effect of adding graphene to epoxy resin used in carbon fiber-reinforced structural strengthening of concrete beams. The thermal and mechanical properties of the epoxy/graphene composite and the pure epoxy resin (reference) were characterized by FTIR, TGA/DTA, and tensile tests. The results showed that the addition of graphene did not alter the thermal behavior, cross-linking, or tensile strength of the resin, maintaining the key mechanical properties of the base material. In addition, graphene significantly enhanced the resin toughness by 107.69%, despite a 20.21% reduction in elastic modulus, indicating an improved capacity for deformation and energy absorption before rupture.

Four-point bending tests allowed comparison of the stress corresponding to first cracking and ultimate failure in concrete beams strengthened with carbon fiber blankets bonded with epoxy, with or without graphene. The results showed statistically similar stress levels for both configurations, which is consistent with the observed failure mode: delamination of the concrete layer rather than detachment of the carbon fiber reinforcement. In this context, the presence of graphene in the matrix could potentially have a greater influence under different failure modes.



Overall, although premature delamination limited the full utilization of the strengthening system, the addition of graphene maintained the critical properties of the epoxy resin while significantly increasing its toughness, suggesting a potential improvement in structural performance. This enhancement could contribute to a reduced risk of brittle fractures, cracking, and delamination of the carbon fiber reinforcement in concrete beams.

5 REFERENCES

ABDI, E. et al. The effect of graphene and graphene oxide on defective single lap adhesively bonded joints. **Journal of Composite Materials**, v. 56, n. 17, p. 2665-2675, July 1, 2022.

ABNT - ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **NBR 5738**: Concrete – Procedure for modeling and curing test specimens. Rio de Janeiro, 2015.

ABNT - ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **NBR 5739**: Concrete – Compression testing of cylindrical test specimens. Rio de Janeiro, 2018.

ABNT - ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **NBR 6118**: Design of concrete structures. Rio de Janeiro, 2023.

ABNT - ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **NBR 12142**: Concrete – Determination of flexural strength of prismatic specimens. Rio de Janeiro, 2010.

ACI (AMERICAN CONCRETE INSTITUTE). ACI 440-2R-08 - State-of-the-art report on fiber reinforcing plastic reinforcement for concrete structures.

ASTM (American Society for Testing and Materials). **ASTM C78/78M**. Test method for flexural strength of concrete (using simple beam with third-point loading). ASTM International, West Conshohocken, PA, 2022, www.astm.org.

BALAGURU, P.; NANNI, A.; GIANCASPRO, J. **FRP composites for reinforced and prestressed concrete structures: a guide to fundamentals and design for repair and retrofit**. Taylor & Francis, 2008.

BARBOSA, L. C. DE A. Infrared spectroscopy in the characterization of organic **compounds**. UFV, 2007.

BIANCHI, O. *et al.* Rheology, curing and time-dependent behavior of epoxy/carbon nanoparticle systems. **Journal of Applied Polymer Science**, v. 141, n. 3, Jan. 15, 2024.

CHEN, L. et al. A general way to manipulate electrical conductivity of graphene. **Chemical Engineering Journal**, v. 462, April 15, 2023.



DA LUZ, F. S. et al. **Graphene-incorporated natural fiber polymer composites: A first overview**. PolymersMDPI AG, July 1, 2020.

DE CICCIO, D.; ASAEI, Z.; TAHERI, F. Use of nanoparticles for enhancing the interlaminar properties of fiber-reinforced composites and adhesively bonded joints— a review. **Nanomaterials**, v. 7, n. 11, p. 360, 2017.

FLOREK, P. et al. Carbon fiber reinforced polymer composites doped with graphene oxide in light of spectroscopic studies. **Materials**, v. 14, n. 8, April 2, 2021.

GUEST, J.; KINLOCH, I. A.; YOUNG, R. J. The role of filler aspect ratio in the reinforcement of an epoxy resin with graphene nanoplatelets. **Journal of Materials Science**, v. 58, n. 23, p. 9473–9485, June 1, 2023.

HEIZA, K. et al. State-of-the-art review: strengthening of reinforced concrete structures - different strengthening techniques. **Sixth International Conference in Nano-Technology in Construction**, 2014.

HSIEH, T. H. et al. The effect of carbon nanotubes on the fracture toughness and fatigue performance of a thermosetting epoxy polym. **Journal of Materials Science**, v. 46, n. 23, p. 7525–7535, Dec. 2011.

HUANG, N. J. et al. Efficient interfacial interaction for improving mechanical properties of polydimethylsiloxane nanocomposites filled with low content of graphene oxide nanoribbons. **RSC Advances**, v. 7, n. 36, p. 22045–22053, 2017.

IRSHIDAT, M. R.; AL-SALEH, M. H.; AL-SHOUBAKI, M. Using carbon nanotubes to improve strengthening efficiency of carbon fiber/epoxy composites confined RC columns. **Composite Structures**, v. 134, p. 523–532, Dec. 15, 2015.

IRSHIDAT, M. R.; AL-SALEH, M. H. Effect of using carbon nanotube modified epoxy on bond-slip behavior between concrete and FRP sheets. **Construction and Building Materials**, v. 105, p. 511–518, Feb. 15, 2016.

IRSHIDAT, M. R.; AL-SALEH, M. H.; ALMASHAGBEH, H. Effect of carbon nanotubes on strengthening of RC beams retrofitted with carbon fiber/epoxy composites. **Materials and Design**, v. 89, p. 225–234, Jan. 5, 2016.

IRSHIDAT, M. R.; AL-SALEH, M. H. Flexural strength recovery of heat-damaged RC beams using carbon nanotubes modified CFRP. **Construction and Building Materials**, v. 145, p. 474–482, Aug. 1, 2017.

IRSHIDAT, M. R.; AL-HUSBAN, R. S. Effect of bond enhancement using carbon nanotubes on flexural behavior of RC beams strengthened with externally bonded CFRP sheets. **Frontiers of Structural and Civil Engineering**, v. 16, n. 1, p. 131–143, Jan.



1, 2022.

KINLOCH, A. J.; YOUNG, R. J. **Fracture behavior of polymers**. Dordrecht: Springer Netherlands, 1995.

LAVORATTI, A.; ZATTERA, A. J.; AMICO, S. C. Mechanical and dynamic-mechanical properties of silane-treated graphite nanoplatelet/epoxy composites. **Journal of Applied Polymer Science**, v. 135, n. 45, Dec. 5, 2018.

PANIGRAHI, A. K. **Strengthening of shear deficient RC T-beams with externally bonded FRP sheets**. ODISHA: NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA, Jan. 2013.

RAFIEE, M. A. et al. Enhanced mechanical properties of nanocomposites at low graphene content. **ACS Nano**, v. 3, n. 12, p. 3884–3890, Dec. 22, 2009.

RAFIEE, M. et al. Significant fatigue life enhancement in multiscale doubly- modified fiber/epoxy nanocomposites with graphene nanoplatelets and reduced- graphene oxide. **Polymers**, v. 12, n. 9, 2020.

REALE BATISTA, M. D.; DRZAL, L. T. Carbon fiber/epoxy matrix composite interphases modified with cellulose nanocrystals. **Composites Science and Technology**, v. 164, p. 274–281, Aug. 18, 2018.

REIS, L. S. N. **On the recovery and reinforcement of reinforced concrete structures**. Belo Horizonte: Federal University of Minas Gerais, Apr. 12, 2001.

RIBEIRO, H. **Synthesis and characterization of nanostructured composites based on chemically modified graphene nanosheets. Preparation, study of structure and physicochemical properties**. Belo Horizonte: Federal University of Minas Gerais - Institute of Exact Sciences, 2015.

SCHUSTER, M. B. **Fracture toughness in epoxy matrix nanocomposites with carbon nanoparticles**. Joinville: State University of Santa Catarina, Dec. 4, 2017.

SHARMA, H. et al. **An overview on carbon fiber-reinforced epoxy composites: Effect of graphene oxide incorporation on composites Performance**. *PolymersMDPI*, 2022.

SHESHMANI, S.; ASHORI, A.; ARAB FASHAPOYEH, M. Wood plastic composite using graphene nanoplatelets. **International Journal of Biological Macromolecules**, v. 58, p. 1–6, 2013.

SILVA, D. D. DA; SANTOS, W. F. DOS; PEZZIN, S. H. Epoxy matrix nanocomposites with reinforcements produced from natural graphite. **Matéria (Rio de Janeiro)**, v. 18, n. 2, p. 1216–1272, 2013.

SILVA, E. M. DE A. et al. Methods for restoration and reinforcement of reinforced concrete structures. **Revista Ibero-Americana de Humanidades, Ciências e Educação**, v. 8, n. 11, p. 2255–2286, Nov. 30, 2022.

TRUONG, G. T.; VAN TRAN, H.; CHOI, K. K. Investigation on mode I fracture toughness of woven carbon fiber-reinforced polymer composites incorporating nanomaterials. **Polymers**, v. 12, n. 11, p. 1–23, Nov. 1, 2020.

WAZALWAR, R.; TRIPATHI, N.; RAICHUR, A. M. Mechanical and curing behavior of epoxy composites reinforced with polystyrene-graphene oxide (PS-GO) core-shell particles. **Composites Part C: Open Access**, v. 5, July 1, 2021.

WANG, H. W. et al. Analysis of effect of fiber orientation on Young's modulus for unidirectional fiber reinforced composites. **Composites Part B: Engineering**, v. 56, p. 733–739, 2014.

WANG, H. et al. Resistance of graphene/epoxy resin—based composite materials to γ radiation damage and their mechanical properties. **Coatings**, v. 13, n. 9, Sept. 1, 2023.
WANG, H.

WIERZBICKI, L. R. **Analysis of the performance of the NSM (Near Surface Mounted) reinforcement technique with carbon fibers in beams subjected to bending**. Curitiba: Federal Technological University of Paraná, 2021.

WU, Q. et al. Constructing a simple anti-sandwich structure on carbon fiber surface for simultaneously strengthening and toughening the interphase of epoxy composites. **Composite Structures**, v. 240, May 15, 2020.

XIONG, S. et al. Enhanced interfacial properties of carbon fiber/epoxy composites by coating carbon nanotubes onto carbon fiber surface by one-step dipping method. **Applied Surface Science**, v. 546, April 30, 2021.

YAN, H. et al. Self-assembly of carbon nanomaterials onto carbon fiber to improve the interfacial properties of epoxy composites. **Journal of Materials Science and Technology**, v. 161, p. 44–49, Oct. 20, 2023.

YUSTE-SÁNCHEZ, V. et al. In-situ cure monitoring of epoxy/graphene nanocomposites by several spectroscopic techniques. **Polymer Testing**, v. 80, Dec. 1, 2019.

ACKNOWLEDGMENTS

The authors thank the UTFPR-CT, CMU-CCT Multi-User Facility infrastructure from Santa Catarina State University's Technological Sciences Center and State University of Santa Catarina (UDESC), Community University of the Region of Chapecó (Unochapecó - SC), and the Polymeric Materials Laboratory (LaMaPo), Department of Chemistry and Biology (DAQBI), Civil Construction Laboratories, Department of Civil Construction



(DACOC), and Chemistry Laboratory of the Technical-Scientific Sector of the Regional Superintendency of the Federal Police in Paraná, for providing their laboratories and equipment.