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Effects of Carbon Fiber on Mechanical Properties of Reactive Powder Concrete

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ABSTRACT The use of fiber generally might change the mechanical properties of concrete in flexural or compressive strength. Reactive powder concrete (RPC) is one of the ultra-high-performance concrete types that has been applied for some constructions. Carbon fiber, having high strength in tensile, also has the potency to improve the physical characteristics of RPC. The purpose of this study is to evaluate the flexural and compressive performance of RPC, focusing on the interfacial binding of carbon fiber. Flexural and compressive tests used samples with dimensions of 40 x 40 x 160 mm were tested in accordance with BS-EN-196-1:2011, which allows to use one of the two broken pieces from the flexural test as the sample. The microstructure surrounding carbon fiber and paste was qualitatively compared using Scanning Electron Microscopy (SEM) in the secondary electron detector mode. Samples were subjected to static pressure at 8 MPa after 1 hour of pouring and heat curing at 240 °C in a dry oven after demolding. Results show that the presence of carbon fiber increased the flexural strength of RPC by up to 28.85% for samples without treatments and up to 14.32% for samples with both treatments. Although carbon fiber increased toughness by 20% and flexural modulus by 6%, it had no effect on the failure mode after reaching the peak load, which remained brittle. On the other hand, the presence of carbon fiber had little effect on compressive strength. Despite the pressure and heat, curing treatments had no effect on enhancing the adhesion between carbon fiber and cement paste, which was indicated by the undamaged surface of carbon fiber. However, the implementation of both treatments on samples might produce RPC with good mechanical properties in flexure.

KEYWORDS RPC, Carbon Fiber, Mechanical Properties, Flexural Strength, Compressive Strength

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1 INTRODUCTION

Reactive Powder Concrete RPC is compositionally different from plain concrete because the RPC mixture uses a high proportion of fine particles <600 µm such as silica fume, quartz sand, or other admixtures, and is entirely without coarse aggregates. The reactive powder components undergo chemical reactions through heat-accelerated hydration of the cement particles, heat-accelerated pozzolanic reactions between Portlandite and amorphous silica from the densified silica fume, and the transformation of tobermorite to xonotlite during heat curing (Cwirzen, 2007). Every variation in composition and treatment affect the mechanical properties of RPC, where most studies on RPC have typically focused on homogeneity and compacted density. Accordance to Ahmed Ali et al. (2021) study, RPC represents a cutting-edge variant of high-performance concrete. It distinguishes itself through its elevated cement content, minimal water content, and the incorporation of fine sand and silica dust. Notably, the resilience of RPC specimens diminishes as the temperature rises. RPC, as described by Richard and Cheyrezy (1995), is an ultra-high-strength and highly ductile concrete achieved through precise aggregate optimization and the use of fine powders, steel fibers (optional), and superplasticizers. Its exceptional compactness gives it remarkable strength and durability, making it suitable for structures near water bodies such as foundations and harbors. According to Ženíšek et al. (2016) and Sanjuán and Andrade (2021), RPC was developed in France in the late 20th century and known for its exceptional strength and durability, with a lifespan of up to 200 years and compressive strength exceeding 150 MPa. RPC offers high compressive strength, toughness, low porosity, and low permeability in comparison to high-performance concrete (HPC). It is a durable and sustainable material suitable for various structural applications.

Previous study by Shi et al. (2019) describes RPC as an ultra-high-performance cement composite with exceptional strength, toughness, durability compared to regular concrete and different admixtures influence mechanical properties of RPC and high-temperature curing can improve its compressive strength. Increasing the fiber volume fraction greatly enhances RPC's tensile properties. The flexural properties of plain concrete generally exhibit a direct correlation with compressive strength, where an increase in compressive strength leads to a corresponding increase in flexural strength (Saloma and Agistin, 2019). However, this correlation does not always hold true for RPC, especially in RPC mixtures containing steel fiber in combi-

nation with high-temperature curing. It has been observed that steam curing significantly increases compressive strength but simultaneously decreases flexural strength (Al-Hassani et al., 2014). RPC is a composite material known for its impressive mechanical properties, such as high compressive and flexural strength. Achieved through the use of blast furnace slag cement and optimized mixing, RPC could further be strengthened by adding steel fibers, resulting in increased compressive and flexural strength (Janus and Grzeszczyk, 2020).

Some researchers have conducted studies examining changes in the properties of RPC by incorporating additional materials. For instance, they aimed to enhance the bonding between fibers and paste (Al-Hassani et al., 2014) and reduce the cement content by replacing it with industrial waste (Yazıcı et al., 2008; Bahedh and Jaafar, 2018). In general, the mechanical properties of concrete, whether it contains fibers or not, are actually influenced by conditions during and after the setting period (Cwirzen, 2007; Tam and Tam, 2012; Zhang et al., 2019). The purpose of incorporating fibers is to enhance the performance of cementitious matrices in terms of tensile strength, ductility, and durability (Johnston, 2006; Alwash and Al-Sultan, 2018). The mechanisms of improvement include an increase in the stress at which the matrix begins to crack, an increase in strain capacity after reaching the peak load and the ability to arrest crack development (Kadhum, 2015; Raheem et al., 2018). The effect of fibers on flexural strength is greater than on compressive strength, and this is dependent on three main factors: the volume of fibers, the physical properties of fibers and the matrix, and the bond between them (Raheem et al., 2018; Hannant, 1998). The addition of fibers in an RPC mixture can improve its flexural performance, but using them in high proportions can increase the cost and reduce the workability of the mixture (Wang et al., 2013; Kinayekar et al., 2014).

In a study conducted by Mahmoud Hama et al. (2021), the addition of steel fibers to RPC was found to improve its ductility, changing its failure mode from brittle to behavior that is more ductile. Steel fibers help hold the concrete together, delaying the formation of cracks and increasing its ability to deform. This increased ductility is attributed to the steel fibers' reinforcement of tensile strength and crack arrest capabilities in RPC. According to Fawzi et al. (2021) study the impact of adding carbon fibers to RPC found that the different proportions of carbon fibers (0.5%, 1.5%, 2.0%) improved compressive strength, flexural strength, density, and reduced shrinkage in RPC. Chemical resistance remained largely unaffected. RPC described as a durable cementitious composite with advanced mechanical and physical properties, including strength and ductility, superior mechanical and physical characteristics, and highlights RPC's exceptional strength and ductility, and it has found applications in diverse construction projects, such as the world's inaugural RPC structure in France and the Sherbrook Bridge in Canada.

There is limited research on RPC properties when carbon fiber is included in its mixture. The influence of pressure and heat curing on the interfacial bonding of carbon fiber is a critical aspect related to enhancing RPC performance. Therefore, it is essential to investigate RPC performance when it contains carbon fiber and undergoes pressure and heat curing treatments. The objective of this study is to assess the flexural and compressive performance of RPC in relation to its interfacial bonding with carbon fibers.

2 METHODS

2.1 Material and composition

In this study, the composition of the RPC mixture adopted as described in Yazıcı et al. (2008), which involved replacing 40%, of the weight of cement with ground-granulated blast furnace slag GGBS. Additionally, steel fiber substituted with carbon fiber with a diameter of 7 µm and a length of 12 mm. This replacement resulted in a significantly higher number of carbon fibers per unit volume compared to steel fibers, given that steel fibers, have a diameter of 120 µm and a length of 60 mm. In terms of the number of fibers per cubic centimeter, carbon fiber offers 21 times the total surface area of steel fiber. This implies that the frictional surface area of 1.0%, the volume fraction of steel fiber is equivalent to that of 0.05% volume fraction of carbon fiber.

The composition of the RPC, by mass, was similar to that of a previous study (Helmi et al., 2018) but included additional carbon fiber, as indicated in Table 1. The components used included Portland Cement (PC) type 1, quartz sand (QS) with three different grades of diameter A: 2.36-1.18mm, C: 0.60-0.30mm, E: 0.15-0.09mm, micro silica fume (SF) grade 940-D, ground granulated blast furnace slag (GGBS), water, and a superplasticizer (SP) made from polycarbonate polymer. The high-performance carbon fiber employed was of type

Table 1. The material composition of RPC per 1 m^3

Material	Amount
Portland cement (kg)	498
Quartz sand (kg)	976
Silica fume (kg)	208
GGBS (kg)	332
Water (liter)	200
Superplasticizers (liter)	55
Carbon fiber (kg)	1.8

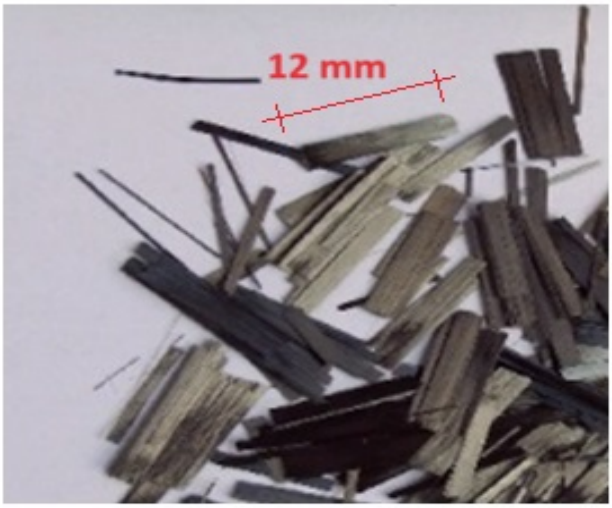

Figure 1 Bundle form of carbon fiber cut in 12mm long

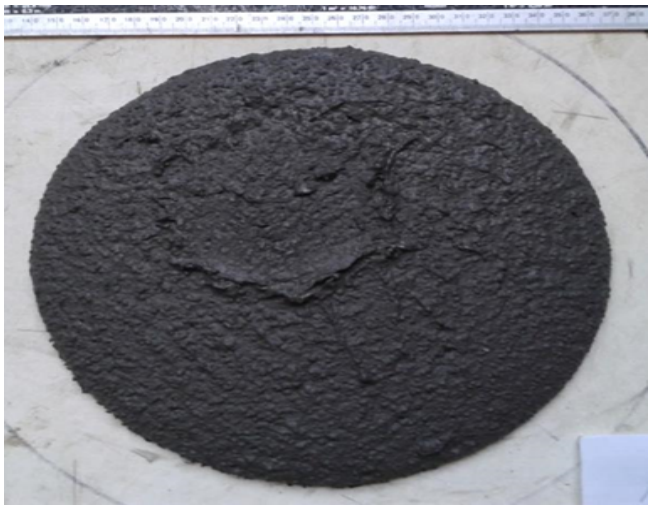

Figure 2 Consistency measurement on RPC fresh mixture

T700SC-120000-50C with a grade of L-Tora-Soficar S.A. France. The factory data sheets provide the following physical properties: diameter equal to 7 µm; tensile strength equal to 4.9 GPa; tensile modulus equal to 230 GPa; elongation equal to 2.10%; density equal to 1.8 g cm^{-3}. The fiber was initially in a thin bundle form and cut to a length of 12 mm using an automatic cutting machine (as shown in Figure 1).

The mixing procedure closely followed the method outlined in the previous study (Helmi et al., 2018). Initially, the dry materials were placed in a mixer operating at a speed of 120 rpm for a duration of 2 minutes. Subsequently, the superplasticizer mixed with water and gradually introduced to the mixer. This is followed by further mixing at a speed of 450 rpm for approximately 10-12 minutes until the mixture achieves a consistent texture. The entire mixing process took approximately 12-16 minutes.

The consistency of fresh RPC mixture was measured immediately after mixing in accordance with ASTM C230 and following the steps of Nambiar and Ramamurthy (2008) by measuring the spread diameter of fresh RPC and comparing it to an initial diameter of 75 mm. Figure 2 shows that the RPC mixture containing carbon fiber appears as plastic flowing and spreadable around 16 cm which was double than initial diameter (75 mm) and higher than the consistency mixture in Yazıcı et al. (2008). Once the mixture reached the desired consistency, it was poured into oiled steel molds, which contained three prisms of sample with a dimension of 40 × 40 × 160 mm.

2.2 Treatments and testing

Two treatments were implemented for the fresh samples: static pressure and heat curing. A static pressure of 8 MPa was applied to the surface of the samples 5 hours after casting and maintained for a duration of 2 days. Heat curing was conducted in a dry convection oven at a temperature of 240 °C for 48 hours. Following the heat curing process, the samples were allowed to cool and subsequently cured in water until the testing time at an average room temperature of 20 °C. Samples identified as follows: (A) for samples without pressure and cured in water; (B) for samples without pressure and heat cured in a drying oven; (C) for samples with pressure and cured in water; (D) for samples with pressure and heat cured in a drying oven.

Samples were tested in flexure by UTM after 28 days (as shown in Figure 3), with a loading rate of 0.1 mm $minute^{-1}$ applied at mid-span, and a clear distance of 100 mm between the simple supports, as specified in BS-EN-196-1:2011. Linear variable differential transformers LVDT, were installed on both sides of the middle span to measure the deflection of the sample during the loading process, enabling the plotting of load and deflection data. Additionally, the compressive strength test, in accordance with BS-EN-196-1:2011 conducted at 28 days using one of the two broken pieces from the flexural test. The contact pressed area of the sample is almost 40 × 40 mm, and the height is 40 mm. Toughness, which is the ability of a material to absorb energy before rupture, was accounted from the area under the load-deflection curve in the flexure test up to 2.5 mm mid-span (Ghosni et al., 2013). It is also possible to define the flexural modulus from this curve using Equation 1 (Horners, 2008) as follows:

$$E_{ff} = \frac{m.l^3}{4.b.d^3} \quad (1)$$

where E_{ff} is the Flexural modulus of elasticity (MPa), m is a gradient of the initial straight-line portion of the

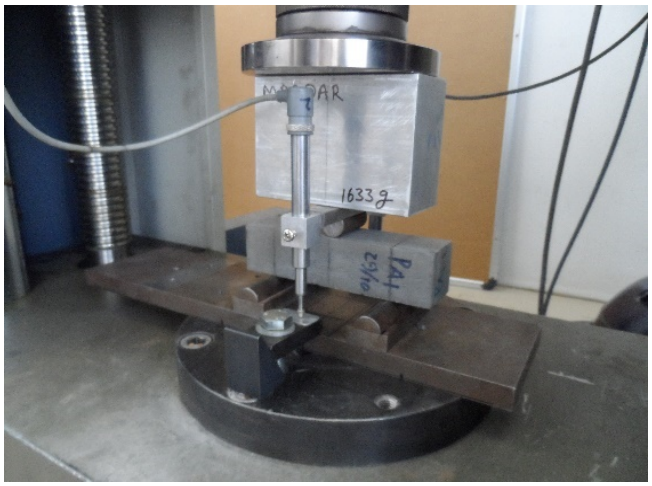

Figure 3 Configuration flexural testing on UTM

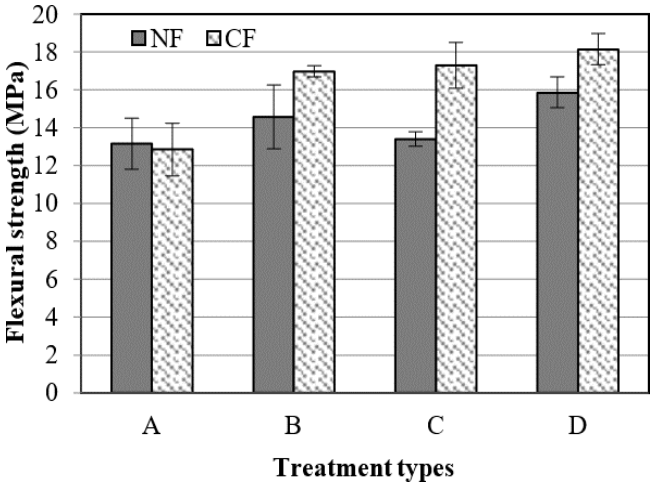

Figure 4 Flexural strength of both RPC non-fiber (NF) and carbon fiber (CF) for all conditions

load-deflection, l is the span of support, b is the width of the beam, and d is the depth of the beam.

3 RESULTS

3.1 Flexural strength

Flexure testing of RPC prisms employed the three-point loading method with a rate of 0.1 mm/min and a clear distance of 100 mm between the supports. The flexural test results for RPC with carbon fiber labeled CF compared with those without fiber labeled NF under four different conditions. Figure 4 displays the average flexural strength of three samples with and without carbon fiber under the same curing conditions. It reveals that carbon fiber had varying influences on flexural strength across the treatments, with -2.37% for A, 16.42% for B, 28.85% for C, and 14.32% for D. Condition A exhibits overlapping error bars, suggesting that NC and NF have similar strengths. Treatment A resulted in the flexural strength of NF being slightly higher than CF. It is supposed to be due to the presence of an entrapped void around fiber and a less dense matrix, which then reduces the flexural due to a decrease in compressive strength. Figure 4 also shows that the flexural strength increased in line with the treatments applied. It seems that the carbon fiber role slightly increased flexural strength for the same treatments, and treatment D had the most influence on strength. However, regarding overlapping error bars, it suggests that NC and NF have similar strengths.

When comparing RPC with carbon fiber to the same mixture under condition A, the commonly used conditions generally improved flexural strength in a range of 30-40%. It is evident that the addition of carbon fiber has a significant impact on the flexural strength of an RPC, mixture when subjected to any of the altered curing conditions. This effect is believed to be due to the mechanism of carbon fibers, which enhance the stress in the matrix before cracking and increase the maximum load in flexure (Johnston, 2006; Yazıcı, 2018). Moreover, the presence of fibers in reinforced concrete can also enhances the bonding between the matrix and bars by impeding crack growth (Alwash and Al-Sultan, 2018).

3.2 Toughness and modulus elasticity

Flexural testing under all curing conditions exhibited brittle failure modes, with samples rupturing after reaching their peak load, and only minimal deformation prior to failure. Consequently, deflection after the peak load could not recorded. To assess the impact of carbon fiber in RPC mixtures, the measurements from three samples under condition D, both NF and CF, also plotted in Figure 5.

The presence of fiber did not seem to have an apparent effect on the failure mode, as it continued to exhibit sudden rupture after reaching the peak load, similar to RPC without fiber brittle failure (as seen in Figure 5). However, the gradient of the CF line increased after the first crack (at a point of about 500 N of force), which also indicates the increase in stiffness. It supposes that the presence of carbon fiber might hold the crack progression till due to fiber in pullout resistance mechanism. In addition, the flexural strength of samples CF increased after pressure and curing treatments were applied, which might increase the compressive strength. It indicates that the pullout resistance was affected by an increase in compressive strength (A. et al., 2022). The improved strain capacity after peak load, observed in RPC with carbon fiber, was not evident in the curve, highlighting a different behavior from RPC with steel fiber (Al-Hassani et al., 2014). This suggests that the behavior of carbon fiber after high-temperature curing is the primary cause of this rupture mode.

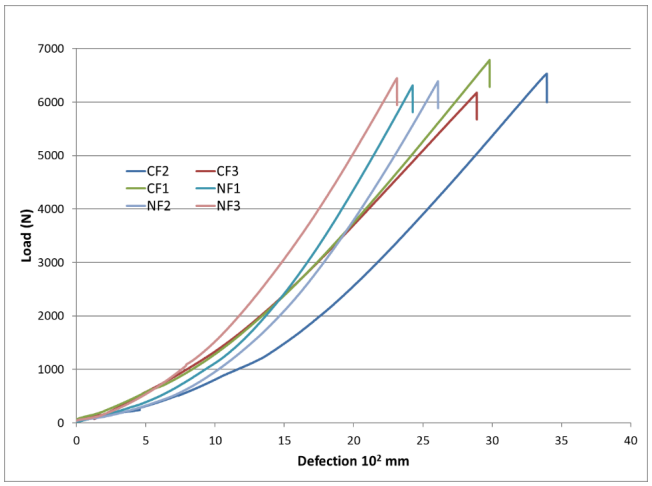

Figure 5 Load and deflection curves for NF and CF with condition D showing immediate rupture after peak load

Figure 6 Failure condition of sample after peak load

It is known that steel fiber has a thermal coefficient of expansion similar to that of plain concrete (Neville, 2018), which is approximately 13.51 $\times 10^{-6}$/°C, whereas carbon fiber has a lower coefficient of expansion (Pradere and Sauder, 2008), around 2.1 $\times 10^{-6}$/°C. When the RPC sample cured at high temperatures and then cooled in the air, the expansion and shrinkage of carbon fiber is less than that of cement paste or steel fiber. This behavior may diminish the bonding mechanism between the paste and the carbon fiber, subsequently reducing the fiber's pullout strength. Moreover, the pullout strength of carbon fiber at ambient temperature is also lower than that of steel fiber, with 1.29 MPa for carbon fiber and 5.48 MPa for steel fiber (Katz et al., 1995). The use of carbon fiber in low-volume fractions of 0.1%, is believed to be an additional factor contributing to the failure occurring shortly after reaching the maximum load (Johnston, 2006). It appears that the weak bonding between carbon fiber and the cement paste, possibly caused by the heat curing process, is a primary factor leading to brittle failures in RPC (as shown in Figure 6).

Toughness quantified as the area under the load-deflection curve up to 2.5 mm of deflection, and the flexural modulus calculated using Equation 1 refer to Table 2. The introduction of carbon fiber into the RPC mixture led to a significant 20% increase in toughness and a slight 6% increase in the flexural modulus. This improvement is likely attributed to the fiber's role in impeding crack propagation and absorbing energy before the sample undergoes complete failure (Johnston, 2006; Raheem et al., 2018). However, the presence of carbon fiber did not appear to have an effect on the failure mode, as the samples still exhibited immediate, brittle failure following the peak load. This Behavior may be linked to an increase in porosity within the paste and at the interface with the carbon fibers. Additionally, the difference in thermal expansion coefficients between carbon fiber and the cement paste play a role during the heat curing process (Pradere and Sauder, 2008; Neville, 2018).

3.3 Compressive strength

The compression test results for NF and CF under all curing conditions are depicted in Figure 7. In condition A, the compressive strength of CF is marginally higher than that of NF. Despite the relatively weak bond between carbon fiber and cement paste, this improvement is actually likely attributed to the role of carbon fiber in preventing random crack propagation. However, since the error bars overlap, it can be assumed that the compressive strength of both NF and CF is similar.

Under condition B, the presence of carbon fiber in the RPC mixture resulted in a marginal 2% increase in compressive strength. However, this difference is not statistically significant when considering the error bars. Notably, the compressive strength of RPC with carbon fiber, subjected to heat curing in a dry oven, shows distinct results when compared to samples with steel fibers that have undergone dry oven curing or steel fibers subjected to autoclave curing (Tam and Tam, 2012). Despite dry oven curing also leading to the formation of xonotlite (Tam and Tam, 2012); it does not significantly enhance compressive strength when the sample contains carbon fiber. This might be attributed to the varying thermal expansion coefficients between carbon and steel fiber, resulting in higher internal thermal stresses with carbon fiber (Szoke, 2006).

Under condition C, there was a slight increase in compressive strength, approximately up to 6%. This increase might attributed to the application of pressure, which could have resulted in the repositioning of the binder particles around the fiber, making them closer and more compacted, reducing the void ratio. This, in turn, could enhance the bond between the cement

Table 2. Toughness and flexural modulus result for NF and CF with condition D

No	Load (N)	Deflection (10^{-2} mm)	Toughness (N.mm)	E_f (MPa)
Type NF				
1	6448	28.1	584	4547
2	6047	27.4	519	4527
3	6448	27.3	500	4330
	Average		535	4468
Type CF				
1	7345	29.1	694	4774
2	6847	27.4	631	4639
3	6719	27.3	606	4742
	Average		644	4718

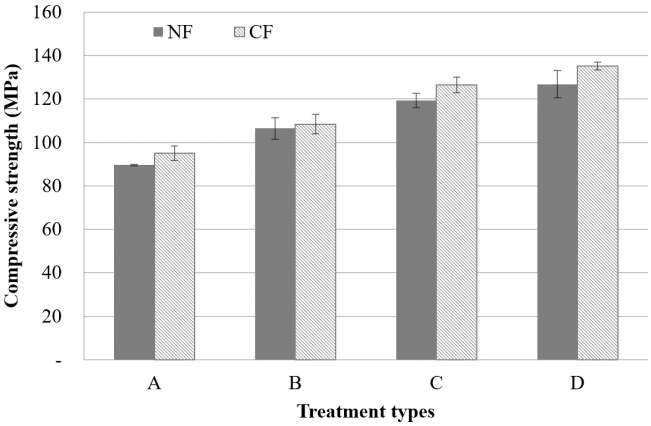

Figure 7 Compressive strength NF and CF for all conditions showing the overlapping of error bars between both.

paste and the fiber. Moreover, the application of pressure may also reduce the porosity of the cement paste (Cwirzen, 2007). This observation supports the explanation provided for condition B, suggesting that the differential expansion of the cement paste and carbon fiber during heat curing might be a factor contributing to the relatively lower compressive strength.

Under condition D, the measured compressive strength exhibited a slight increase of up to 7%. However, the influence of carbon fiber, in this case, is somewhat diminished due to the significant difference in the thermal expansion coefficient between the carbon fibers and the cement paste, as previously explained, and believed to be an additional factor contributing to the failure occurring shortly after reaching the maximum load (Johnston, 2006). It appears that the weak bonding between carbon fiber and the cement paste, possibly caused by the heat curing process, is a condition B. These compressive strength results are statistically similar, as indicated by the overlapping error bars. Regarding the result of NF and CF in Figure 7, the presence of carbon fiber had little effect on compressive strength, and the increase in strength was mostly affected by treatments. The compressive strength of both NF and CF without treatments (condition A) was less than 100 MPa and increased after treatments, becoming over 100 MPa. Even both treatments (condition D) resulted in the compressive strength of RPC without carbon fiber (NF) being better than C-CF, B-CF, and A-CF. It indicates that condition treatment has most affected on compressive strength than CF presence. Nonetheless, condition D is totally recommended as a method to produce RPC samples with favorable properties from both a mechanical and microstructural perspective.

There are two distinct advantages to applying condition D: first, the application of pressure can compact the matrix, thereby enhancing the capacity of the added carbon fiber to mitigate the initiation of micro defects within the concrete and prevent subsequent bridging cracking (Chen and Liu, 2004). Second, heat curing promotes pozzolanic reactions and transforms C-S-H phases from tobermorite to xonotlite, (Cwirzen, 2007).

3.4 Interfacial binding between matrix and fiber carbon

In general, pressure curing reduces the bulk density of the paste, whereas heat curing further fills micro-pores with hydration products resulting from the pozzolanic reaction. To assess the effects of both treatments, the microstructure of the interfacial zone Surrounding carbon fibers qualitatively compared using Scanning Electron Microscopy (SEM) in secondary electron detector mode, as illustrated in Figure 8.

Figure 8 (a) displays the surface of the carbon fiber at the fracture surface of the specimen without any treatment (A). The fibers surface appears remarkably smooth without any scratches or signs of deboned paste, indicating a poor adhesion between the cement paste and the carbon fiber. In Figure 8 (b), the surface of the paste depicted after the carbon fiber has pulled out during the prism's rupture. This surface shows numerous micro-pores with a diameter of around 0.1 190 µm. Applying pressure and heat curing still appears to have no significant effects on the surface of the carbon fiber, as seen in Figure 8 (c). However, both treatments have resulted in the cement paste becoming notably denser, along with longitudinal crack propagation, as observed in Figure 8 (d).

These observations align with the previous discussion regarding the behavior of RPC in flexural tests, where brittle rupture and a loss of strength were then observed after reaching the peak load. It appears that the treatments applied to RPC specimens have limited effectiveness in enhancing the adhesion between carbon fibers and the cement paste. Furthermore, the undamaged surface of the carbon fiber suggests a primarily friction-based bonding mechanism with a constant rate of fiber pullout (Katz et al., 1995). The main limiting factor in brittle rupture appears to be the adhe-

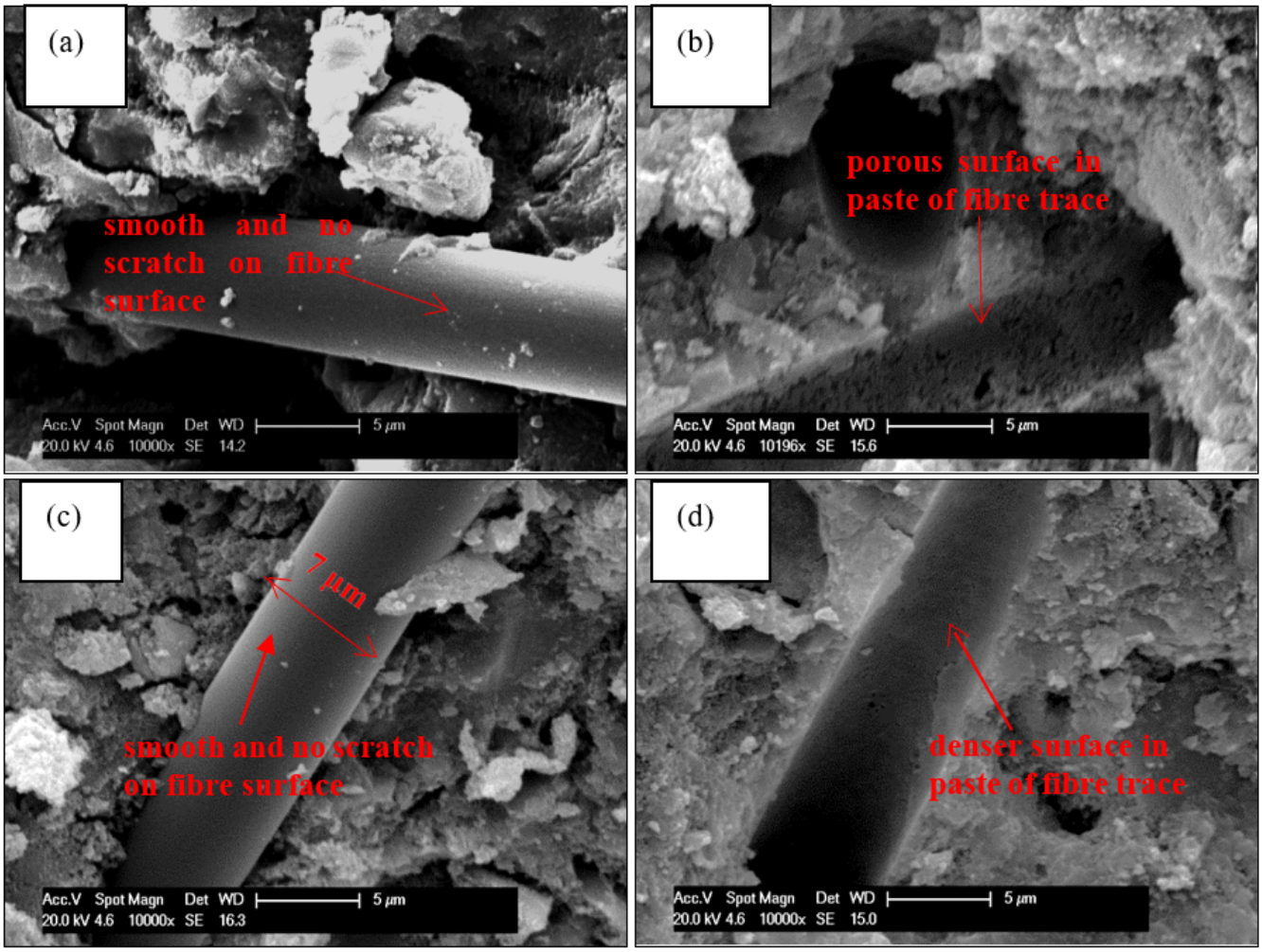

Figure 8 Interfacial carbon fiber for treatment A and D: (a) and (b) are surfaces of carbon fiber and cement paste in treatment A; (c) and (d) are the surface of carbon fiber and cement paste in treatment D.

sion between carbon fiber and cement paste, while the pressure and heat treatments only contribute to the enhancement of paste properties rather than the composite as a whole. This limitation might potentially to improved by implementing treatments that focus on the preparation or functionalization of the carbon fiber surface, such as heating, ozonation, or NaOH solution etching (Cwirzen, 2007).

4 CONCLUSION

The addition of carbon fiber to the RPC mixture significantly improved the flexural strength of RPC, with an increase of up to 40% observed for D treatments. However, it did not have an apparent effect on the failure mode of RPC, which continued to exhibit sudden rupture after reaching the peak load brittle failure, similar to RPC without carbon fiber. This suggests that the difference in thermal expansion coefficients between carbon fiber and cement paste during heat curing conditions were the cause of this brittle rupture. The presence of carbon fiber also increased the toughness by 20% and the flexural modulus by 6%. This enhancement would be attributed to the role of fibers in suppressing crack progression, which resulted in the absorption of rupture energy before the complete separation of the sample occurred. Despite these improvements in flexural properties, the influence of carbon fiber appeared to have a limited effect on compressive strength under all treatment conditions. The treatments applied in this study had little effect on enhancing the adhesion between carbon fibers and cement paste. Consequently, brittle rupture occurred after reaching the peak load, ultimately leading to fiber pullout as the mode of failure. However, it should be noted that both pressure and heat-curing treatments could yield low fiber fraction RPC mixes with favorable flexural properties. Pressure treatment during curing compacts the matrix and enhances the capacity of the added carbon fiber to mitigate the initiation of microfractures and prevent subsequent bridging cracking.

DISCLAIMER

The authors declare no conflict of interest.

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