Experimental Study of Polyvinyl Alcohol (PVA) Fiber Reinforced Concrete under Cyclic Loading

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Abstract. Fiber reinforced concrete (FRC) elements are widely used in applications subjected to cyclic loadings such as pavements, wind towers and tunnel-linings. The FRC improves the behavior of structures subjected to these loadings by controlling the crack opening and the damage propagation and thus can withstands thousands or millions of cycles during their service life. The purpose of this work is to evaluate the mechanical behavior of concrete reinforced with PVA fibers comparing to polypropylene fibers, quantifying the damage and the development of cracks under three point bending cyclic and quasi-static tests. The quasi-static tests results indicate that the addition of PVA fibers increases ductility and toughness, as it is already known for polypropylene macro fibers. Moreover, for the cyclic tests, the fibers contribute to the stiffness maintenance reducing the damage in the material and consequently reducing the crack width and propagation. Finally, when comparing the PVA-FRC with the polypropylene fiber reinforced concrete (PP-FRC), it was found that the PVA sample presented lower damage during the cycles and therefore resulting in a smaller CMOD variation.

Keywords: fiber reinforced concrete, cyclic loadings, PVA fibers.

1 Introduction

Concrete is one of the most widely used construction materials all over the world since centuries ago [1]. The concrete can be molded into many shapes or sizes, with considerable high compressive strength and durable behavior. These properties combined with relatively low cost, make concrete one of the most popular materials in the construction industry. However, the concrete brittle nature is a disadvantage mostly for its tensile strength which provides low resistance to crack opening and propagation [2].

Since the second half of the 20th century, the addition of fibers in concrete has been studied to overcome its brittle behavior. The fiber reinforced concretes (FRC) can support loads even in cracked conditions during the service life when they are designed to it or in an accidentally induced crack. FRC elements are widely used in applications submitted to cyclic loadings as offshore structures [3], wind towers [4], tunnel linings [5], and pavements [6,7].

Cyclic loads develop tensile stresses which can start the crack, and its propagation results in the loss of performance. The potential collapse is reasonably higher if the cracks are already developed in the structure [8,9]. The crack-opening increment is increased by each cycle turning microcracks into macrocracks and occasional cracking in the fiber-matrix interface that leads to a reduction in the fiber-concrete bond and residual strength [10].

Considering the application of the PVA-FRC with structural responsibility as elements under high-cycle loads (10^3-10^5) as airport pavements and railway sleepers [11], and the limited studies on flexural cyclic tests reveals that a broader understanding of the crack-opening evolution and post-cycle residual flexural resistant strength in the PVA-FRC is necessary. Therefore, this work aims to investigate the improvement in the behavior of the concrete with the addition of PVA macrofibres when subjected to cyclic flexural loads for non-cracked and pre-cracked conditions.

2 Experimental Program

2.1 Materials and mix design

The concrete mixture materials used to produce specimens for all the tests performed in this investigation are Portland cement CPV-RS, locally available fine and coarse crushed aggregates. The compressive strength of this matrix was 50 MPa, characterized according to NBR 5739 [12]. Other constituents are the straight PVA fibers RF4000® produced by Kuraray and polypropylene fibers, superplasticizer, polyfunctional and potable water. For the fine aggregates, the natural sand passed through a 4.75 mm sieve and had a fineness modulus (FM) of 2.58 and the stone sand also passed through a 4.75 mm sieve with a FM of 2.02. Two different types of coarse aggregates were used: one with a maximum diameter of 9 mm and the other with 19 mm. The properties of the fibers, as provided by the suppliers are presented in Table 1. The superplasticizer, ADVA® 753, and the polyfunctional MiraSet® 818 supplied by GCP Applied Technologies, and conforming to the requirement of NBR 11768 [13], were used to adjust the workability of the mixes. The FRC mixture proportions are shown in Table 2.

For the mixing procedure, dry materials in the order of natural sand, stone sand, cement, and coarse aggregate were added to the concrete mixer (30 l or 400 l, depending on the amount of concrete), mixed for one minute before 70% of the water was added. Then the remainder of the water was added with the superplasticizer. Further mixing with all the constituent materials, except the fibers, was done for about 5 min. The specimens without fibers were cast after this stage. However, for the FRC mixture, the fibers were gradually added over a minute to ensure they were well distributed and then mixed for 2 min.

Table 1. Properties of the fibers

Property	RF4000®	Polypropylene
Length (mm)	30	58
Aspect ratio	45	85
Tensile strength (MPa)	900	600
Modulus of elasticity (GPa)	23	7

Table 2. Mixture composition

Material type	Reference
Cement (CPV-RS)	380
Natural Sand	675
Stone Sand	136
Coarse Aggregate (ϕ=9mm)	250
Coarse Aggregate (ϕ=19mm)	650
Water	160
Superplasticizer	3,80
Polyfunctional	1,90

2.2 Mold and specimen preparation

In this study, prismatic specimens as recommended by EN 14651 [14] (550 x 150 x 150 mm) were used for flexural samples molding. Both molds were metal and prepared with a release agent. At the end of the casting, a plastic film was placed on the upper face of the prism, the face exposed to the air, to avoid excessive water loss in the early ages. The specimens were allowed to cure under controlled temperature and humidity for 28 days when testing commenced. Prior to the tests, the specimens were notched at the bottom surface to attach a clip gauge in order to record the crack mouth opening displacement (CMOD) during the tests.

3 Test setups and programs

In this study, it was used the three-point bending test setup recommended by EN 14651 [14], with 500 mm spacing between supports, as seen in Figure 1. The tests were performed with non-cracked and pre-cracked specimens in order to understand the effects of the cyclic loads in the crack formation and propagation, based on the literature [15].

Figure 1. Three-point bending test setup

As described in the experimental program, variations of the fiber type were used in addition to reference plain concrete. The PVA-FRC mixture used 10kg/m³ of the RF4000 PVA fibers while the PP-FRC used 5kg/m³ of the PP fiber. The identification of each mix is shown in Table 3.

Table 3. Mixes identification

Identification	Characteristics
REF	Reference Plain Concrete
RF4-10	10kg/m³ PVA RF4000 fibers
PP-5	5kg/m³ PP fibers

3.1 Non-cracked specimens

For the non-cracked specimens, a sinusoidal cyclic load with a frequency of 6 Hz was applied for 100k cycles with the maximum cycle load (P_{up}) of 70% of the average load at the limit of proportionality (LOP) of monotonically tested samples. The minimum cycle load (P_{lw}) was defined by considering an amplitude ratio of 0.3 ($R=P_{lw}/P_{up}=0.3$). The evolution of the CMOD through the cycles was recorded. Finally, immediately after the end of the cycles, the specimens were tested monotonically to compare the residual strength capacity post-cycles with the quasi-static tests.

3.2 Pre-cracked specimens

The specimens were pre-cracked with a constant CMOD rate of 0.05 mm/min up to a total CMOD of 0.5 mm. The load corresponding to this displacement was recorded and 70% of this load is set as the maximum cycle load (P_{up}). The minimum cycle load (P_{lw}) was defined by considering an amplitude ratio of 0.3 ($R=P_{lw}/P_{up}=0.3$), as it was done for non-cracked specimens. After the pre-cracking phase, without removing the specimen from the setup, a 6 Hz sinusoidal cyclic load, ranging from P_{up} to P_{lw}, was applied to the specimen and the evolution of

CMOD was recorded. When the total of 100k cycles was reached, the cyclic load was interrupted and the specimens were loaded at a constant CMOD rate of 0.2 mm/min up to CMOD of 4.0 mm.

4 Tests results and discussion

For the non-cracked specimens cyclic three-point bending tests, the maximum cycle load applied was 9.8 kN and the minimum cycle load was 2.9 kN. The hysteresis loops over the cycles are shown in Figure 2. The evolution of CMOD during the cyclic tests of all specimens increases rapidly as the cycles increases without macrocrack formation. However, the FRC samples showed smaller increments of CMOD over the cycles than the plain concrete samples. The PVA-FRC showed evolution 46% smaller and the PP-FRC presenting 20% smaller than the plain concrete. Still, it can be verified for the plain concrete samples a greater decrease in stiffness than the FRC specimens.

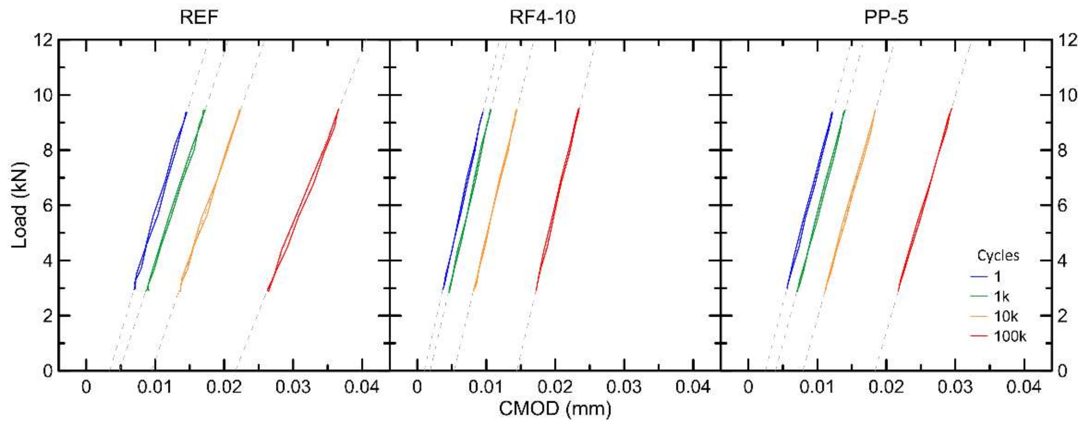

Figure 2. Non-cracked specimens' hysteresis loops over the cycles

After the 100k cycles, the specimens were subjected to quasi-static tests, and their remaining residual strength was compared to the control typical stress vs. CMOD curves, as seen in Figure 3. In general, the post cycles curves for all the specimens did not show a decrease in the residual strength after 100k cycles. Moreover, Table 4 presents the summary for the non-cracked cyclic and quasi-static tests with the $CMOD_1$ and $CMOD_{100k}$ values for the 1st and the 100kth cycle respectively, the maximum residual strength post-cycle ($f_{res,PC}$) and a ratio between this maximum post-cycle strength and the control maximum strength (f_{Cmax}).

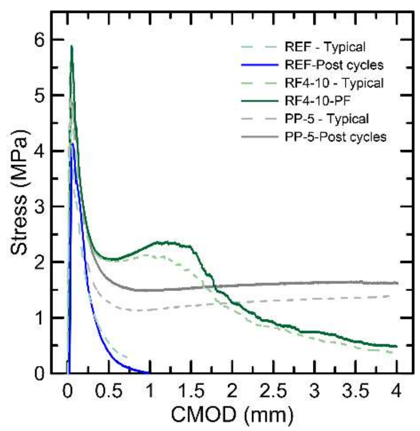

Figure 3. Non-cracked specimens' stress vs. CMOD curves comparison

Table 4. Non-cracked tests summary

Sample	$CMOD_1$ (mm)	$CMOD_{100k}$ (mm)	$f_{res,PC}$ (MPa)	$f_{res,PC}/f_{Cmax}$
REF	0.014	0.037	4.13	0.950
RF4-10	0.009	0.023	5.88	1.080
PP-5	0.012	0.029	4.88	0.990

For the pre-cracked specimens cyclic three-point bending tests, the specimens were subjected to a pre-cracking step with a constant deformation test up to CMOD = 0.5 mm. From this step were obtained the maximum cycle load applied for the PVA-FRC which was 6.15kN while for the PP-FRC was 2.85kN due to the load capacity at the 0.5 mm crack opening. As the reference plain concrete does not show residual strength after the cracking, this sample was not tested. The hysteresis loops over the cycles for the pre-cracked tests are shown in Figure 4. Yet, the presented normalized load values, also in Figure 4 represent the percentage of the load at CMOD = 0.5mm applied to each specimen over the cycles. The evolution of CMOD during the cyclic tests increases more rapidly for the PP-FRC showing CMOD increments 16% higher than the PVA-FRC at the 100kth cycle.

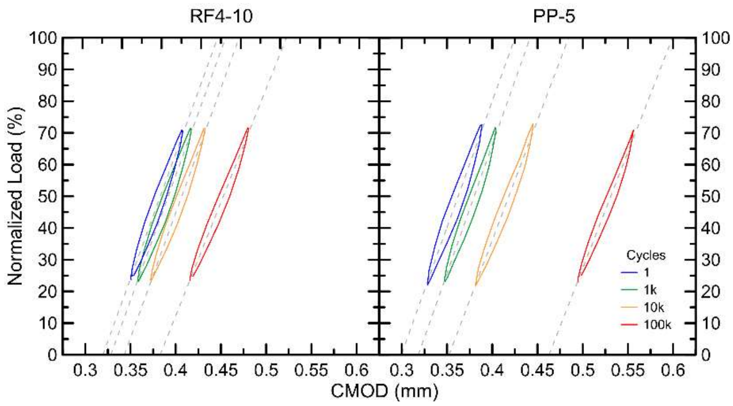

Figure 4. Pre-cracked specimens' hysteresis loop over the cycles

After the 100k cycles, the specimens were subjected to a quasi-static test with a constant deformation rate of 0.2 mm/min until CMOD = 4.0 mm. As it was mentioned for the non-cracked samples, this stage was done in order to compare its remaining residual strength with the typical stress vs. CMOD curves for monotonically tested samples as seen in Figure 5. The post-cycle curves did not show a reduction in the residual strength after 100k cycles.

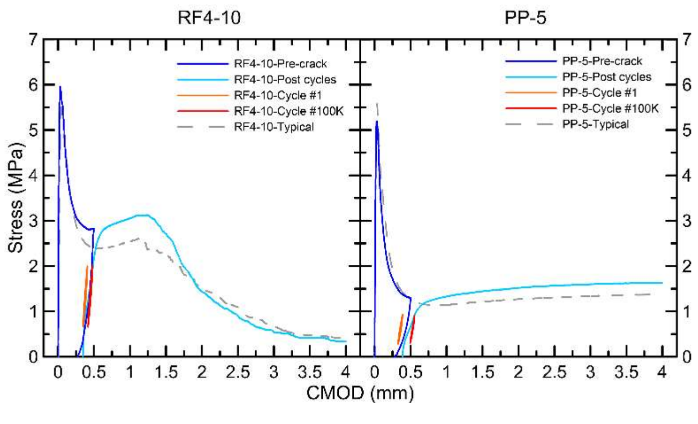

Figure 5. Pre-cracked specimens' hysteresis loop over the cycles

Table 5 presents the summary for the pre-cracked cyclic and quasi-static tests with the $CMOD_1$ and $CMOD_{100k}$ values for the 1st and for the 100kth cycle respectively, the maximum residual strength post-cycle ($f_{res,PC}$).

Table 5. Pre-cracked tests summary

Sample	P_{up} (kN)	$CMOD_1$ (mm)	$CMOD_{100k}$ (mm)	$f_{res,PC}$ (MPa)
RF4-10	6.15	0.407	0.481	3.13
PP-5	2.85	0.389	0.556	1.63

5 Conclusion

This work presented the improvement in mechanical and fatigue properties of the PVA fiber reinforced concrete subjected to cyclic loads, considering non-cracked and pre-cracked conditions and comparing it to the PP-FRC response. The CMOD evolution over the cycles was similar in all samples characterized, regardless of the type of the added fiber or plain concrete.

For the non-cracked specimens, the FRC samples showed less increase in the CMOD value than the reference plain concrete. For all the specimens, the maximum strength and the residual strength did not show reduction after the 100k cycles compared with a monotonic result.

For the pre-cracked specimens, the PVA-FRC showed less increase in the CMOD value than the PP-FRC. The residual flexural strength of the specimens subjected to the cycles is equivalent to the quasi-static tests, with no clear difference observed in terms of strength. These results indicate that a small or no damage was induced to the FRC by the cycles.

Finally, the addition of fibers in the concrete reduces the crack opening and increases the stiffness of specimens submitted to cyclic loads.

Acknowledgements. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nivel Superior – Brasil (CAPES) – Finance Code 001, by Brazilian funding agencies FAPERJ and CNPq, by Lafarge Holcim, with the donation of de CPV cement and by Kuraray, with the donation of the PVA fibers.

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