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Evaluating shrinkage and mechanical performances of polypropylene hybrid fibers reinforced mortar

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Abstract. The shrinkage and the mechanical properties of polypropylene hybrid fiber reinforced mortar PHFRM were investigated in this study. Mortars were prepared with limestone crushing sand, Portland cement and polypropylene hybrid fibers PHF. Two types of virgin fibers, having the same length (30 mm) were used for reinforcing test mortars, fibers in diameter of 0.45 mm, used by PLAST BROS factory of Bordj Bou Arreridj (Algeria) for the fabrication of brooms (for household cleaning) and fibers in diameter of 0.25 mm, available on the market, having multiple applications. In this investigation, it was aimed to study the total and autogenous shrinkage, the flexural and compressive strength of mortars based on hybrid fibers. As a result, PHF have negatively affected the mortar workability. However, shrinkage risk was reduced and coarser fibers (PF45) were most effective for reducing shrinkage risk. The mechanical performances and the ductility of PHFRM were also enhanced.

Keywords: autogenous shrinkage; hybrid fibers; mechanical strength; mortar; polypropylene fibers; total shrinkage

1. Introduction

The high difference in humidity between the fresh concrete and the external environment is one of the main causes of cracking. This is due to the rapid drying of the surface of concrete, causing by the premature evaporation of water, which significantly increases the cracking risk. Under unfavorable conditions of conservation, these cracks increase in the time constituting easy ways for penetration of aggressive agents that deteriorate the material. It is well known that reinforcing concrete by fibers is a good solution to control the creation and the evolution of cracks and to offer durable construction materials. Many types of fibers, as metallic, synthetic, mineral and vegetable fibers can be used in concrete, depending on its application. According to some researches (Hsie *et al*. 2008, Alwesabi *et al*. 2021), it seems that hybrid fibers are more effective in approving the behavior of materials and in reducing cracks risk than single fiber type. The hybridization is obtained by the combination of more than one type of fiber, such as steel and polypropylene fibers, short

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straight and long hooked-end steel fibers, micro and macro polypropylene fibers, basalt and polyolefin fibers, carbon and glass fibers, etc. Numerous studies were conducted on the effect of the hybridization of fibers on the concrete performances (Vandewalle 2006, Yildirim *et al*. 2010, Dawood and Ramli 2011, Hameed *et al*. 2013, Silva *et al*. 2013, Karthik and Maruthachalam 2015, Krūmiņš and Zesers 2015, Shaikh and Taweel 2015, Corinaldesi *et al*. 2016, Zhou *et al*. 2018, Naraganti *et al*. 2019, Smarzewski 2019, Caggiano *et al*. 2020, Fan *et al*. 2020, Madhumitha and Kumar 2020, Mallinadh *et al*. 2020, Nuaklong *et al*. 2020, Ramesh *et al*. 2020, Shi *et al*. 2020, Koksal *et al*. 2021, Shaaban *et al*. 2021, Zhang *et al*. 2021). The use of hybrid fibers ensures synergetic gain, depending on the properties of each fiber. Through their experimental study, Sivakumar and Santhanam (2007) confirmed that hybrid fibers (hooked steel, polypropylene, polyester and glass fiber) were more effective for reducing cracking compared to individual steel fibers. Also, Caggiano *et al*. (2016) have concluded that the combination of steel and polypropylene fibers enhances perfectly the post-cracking behavior of matrices and can respond to specific structural requirements.

Synthetic fibers of polypropylene are among the most appreciated and used fibers for reinforcing concrete thanks to their excellent properties, such as low weight, high deformation, excellent chemical resistance, no ability to absorb water, no ability to chemically react with cement and low production cost. Polypropylene fibers can also enhance the fire resistance of concrete, as reported in the study of Bin *et al*. (2020). The cost of construction can be reduced by the use of synthetic fibers as a substitution of steel rebar and steel mesh (Mohajerani *et al*. 2019). In civil engineering field, many promising technical uses can be offer by the application of polypropylene fiber reinforced concrete, as the recent investigation of Blazy (Blazy and Blazy 2021) that proposes its application in public spaces, for creating decorative pavements, fountains, sculptures, artificial rocks and beaches, exotic landscapes, door surrounds, and skateparks. Due to their good dispersion in the concrete, the fibers of polypropylene can perfectly control the plastic shrinkage cracks (Banthia and Gupta 2006, Islam and Gupta 2016, Bertelsen *et al*. 2019) and prevent cracking development (Yousefieh *et al*. 2017).

For the reinforcement of tested mortar, polypropylene hybrid fibers PHF were used. The hybridization was obtained by virgin fibers of polypropylene, having the same length (30 mm); fibers in a diameter of 0.45 mm produced by PLAST BROS factory of Bordj Bou Arreridj, in Algeria, using for the fabrication of brooms (for household cleaning) and fibers in diameter of 0.25 mm, available on the market and having many applications.

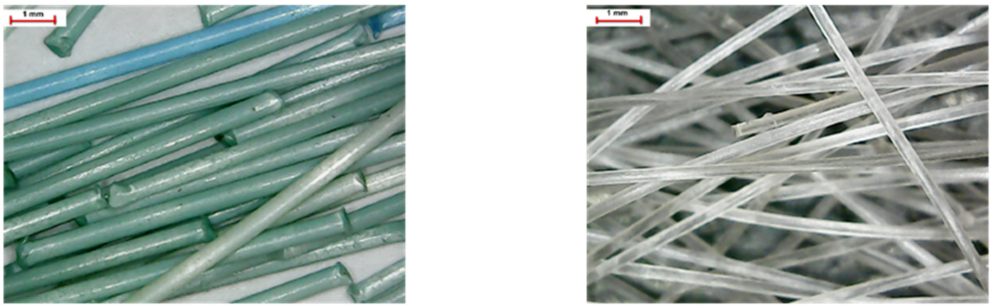
This study is conducted for investigating the effect of the introduction of polypropylene hybrid fibers PHF on the total and autogenous shrinkage and on the flexural and compressive strength of mortars.

2. Experimental program

Two types of virgin polypropylene fibers were used, fibers with a diameter of 0.45 mm (noted PF45) used for the fabrication of brooms (for household cleaning) by PLAST BROS factory of Bordj Bou Arreridj, in the east of Algeria and fibers with a diameter of 0.25 mm (noted PF25), available on the market, having multiple applications. The natural look and the scanning electron microscope of used fibers are shown in Figs. 1 and 2, respectively. Fig. 3 illustrates the experimental setup of tensile testing and the resulting tensile stress-strain curve is shown in Figs. 4(a)-(b) for PF45 and PF25, respectively. Table 1 gives the different properties of PF45 and PF25 fibers. Limestone sand

(a) PF45 (b) PF25

Fig. 1 Natural look of the used polypropylene fibers



(a) PF45 (b) PF25

Fig. 2 SEM magnified image of the used polypropylene fibers

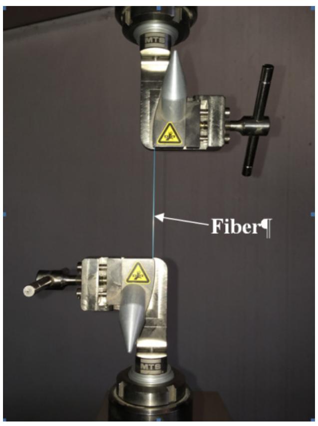
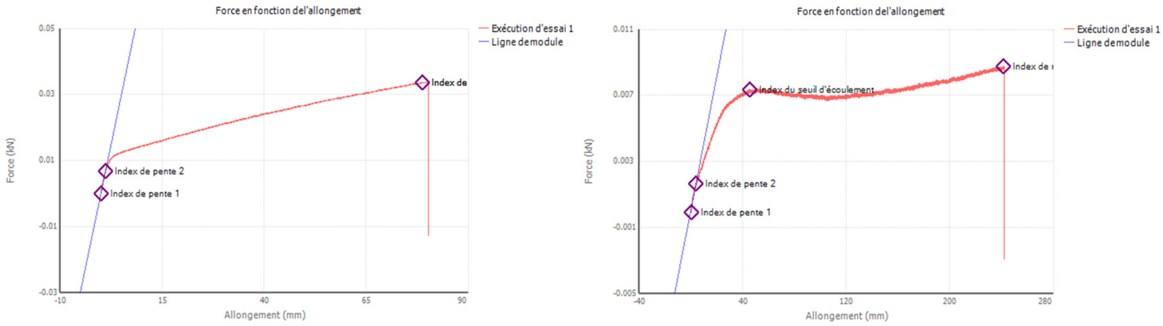


Fig. 3 Experimental setup of tensile testing of fibers

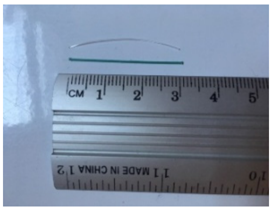
(S) from Ouazzane crushing station, situated in the north of Laghouat and type II Portland cement CEM II/B-L 42.5 N were also used for preparing test mortars. The characteristics and the granular distribution of used sand are given in Table 2 and Fig. 5, respectively. For obtaining workable mixes, a superplasticizer (SP), type SIKA VISCORETE TEMPO 12, fabricated in Algeria by SIKA EL



(a) For PF45 (b) For PF25

Fig. 4 Resulting tensile stress-strain curve of tensile testing of the used polypropylene fibers

Table 1 Properties of used fibers

Properties	PF45	PF25
Nature	Polypropylene (Thermoplastic)	Polypropylene (Thermoplastic)
Surface Morphology	Smooth	Smooth
Cross-section	Circular	Circular
Diameter (mm)	0.45	0.25
Length (mm)		
Specific gravity (g/cm^3)	0.99	0.99
Water absorption	None	None
Melting temperature (°C)	280 – 300	180 – 260
Tensile strength (MPa)	214	184
Elasticity modulus (GPa)	1.90	0.45

DJAZAIR was used. A dosage of 1% by weight of hybrid fiber was used for reinforcing mortar. To prevent the formation of fiber balls during mixing operation and ensure a good dispersion of fibers into the matrix, the mixing process showed in Fig. 6 was adopted, with adding fibers in the end by hand. The water/cement (W/C) ratio was maintained constant for all mixes.

Table 3 shows the composition of the six different mixtures tested in the present work. As reported in other experimental investigations (Belferrag *et al*. 2013, Söylev and Özturan 2014, Adnan and Dawood 2020, Seshaiah *et al*. 2021), polypropylene fibers negatively affect the mortar workability (see Fig. 7). The presence of PF25 and PF45 fibers increases the superplasticizer dosage (Table 3) and the increase varies between 38, 40, 45, 55 and 71% in PHFRM-1-0, PHFRM-0.75-0.25, PHFRM-0.5-0.5, PHFRM-0.25-0.75 and PHFRM-0-1, respectively, compared to control mortar. By comparison to other mixes, mortars prepared with more fine fibers (PF25) need more superplasticizer for reaching the same workability. This behavior is due to the high specific surface

Table 2 Properties of used sand

Nature	Crushed limestone
Specific gravity (g/cm^3)	2.60
Bulk density (g/cm^3)	1.49
Fineness modulus	2.45
Visual sand equivalent (%)	64
Methylene blue value V_B	0.14
Water absorption (%)	6.23
Percentage of fines < 80 µm (%)	22

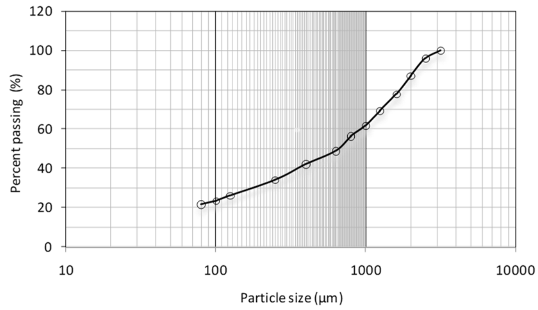


Fig. 5 Granular distribution of used sand

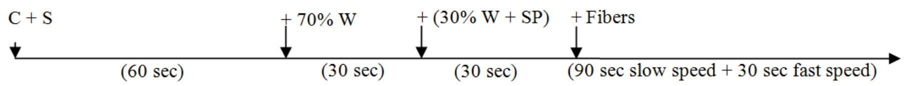


Fig. 6 Mixing process

of finer fibers (PF25), with regard to coarser ones (PF45).

Prismatic specimens (40×40×160) mm were moulded and covered by a plastic film. After demoulding, specimens used for shrinkage tests were conserved in uncontrolled environment (T = 20 ± 5°C and RH = 20 ± 5%) and those used for mechanical tests were stored in controlled chamber

Table 3 Mortar mixes (g)

Mixes	C	S	W	PF45	PF25	SP	W/C
CM	450	1350	247.5	00	00	4.2	0.55
PHFRM-1-0	450	1350	247.5	20.5 (100%)	00	5.8	0.55
PHFRM-0.75-0.25	450	1350	247.5	15.4 (75%)	5.1 (25%)	5.9	0.55
PHFRM-0.5-0.5	450	1350	247.5	10.3 (50%)	10.3 (50%)	6.1	0.55
PHFRM-0.25-0.75	450	1350	247.5	5.1 (25%)	15.4 (75%)	6.5	0.55
PHFRM-0-1	450	1350	247.5	00	20.5 (100%)	7.2	0.55

CM: control mortar; PHFRM-0.75-0.25: mortar reinforced by 75% of PF45 and 25% of PF25

Fig. 7 PHFRM in fresh state

Fig. 8 Autogenous shrinkage test

at 22°C and a relative humidity of 90%. To avoid any humidity exchange with external environment, specimens used for autogenous shrinkage test were covered by aluminum film as showing in Fig. 8. The measurements of shrinkage were carried out from the first day to 28 days for autogenous shrinkage and to 90 days for total shrinkage. The compressive and the flexural strength were tested at 28 days of age, according to standards EN 196-1.

3. Results and discussions

3.1 Total shrinkage

Fig. 9 shows that the total shrinkage evolves quickly during the first 72 hours for all mortars and achieves almost 50% of the maximum values obtained at 25 days aging. The reduction of the total shrinkage observed beyond 25 days has reached 20% at 90 days with regard to the maximum values. The important evolution of total shrinkage, especially at early age is probably due to the conservation conditions, a temperature of 20°C and a relative humidity of 20% accelerate the desiccation of mortars and then increase the shrinkage risk. It is observed that generally the presence of polypropylene fibers reduces the shrinkage, as confirmed by the findings of the previous study of

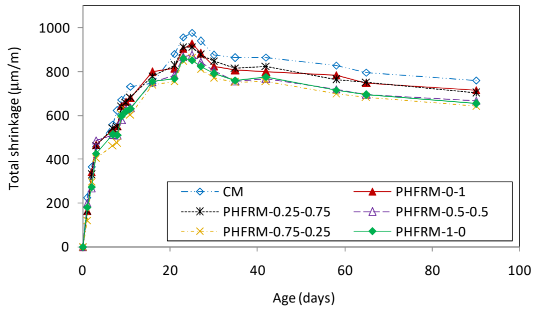


Fig. 9 Total shrinkage development in different mortars

Bendjillali *et al*. (2019). By comparison to control mortar, PHFRM-0.5-0.5, PHFRM-0.75-0.25 and PHFRM-1-0 have the lowest total shrinkage, with a reduction of 14% in average after three months of age. The beneficial effect of fibers, especially coarser fibers (PF45) to reduce the shrinkage is due to their high capacity to prevent cracking by their sewing action. Similar result was reported by other researches (Branch *et al*. 2002). Also, the easy implementation of mortars containing more of coarser fibers (PF45) and the better dispersion of these fibers in the matrix comparing to finer fibers (PF25) positively participate for improving the shrinkage control. According to the obtained results, the effect of fibers on the total shrinkage is more appreciable during the first day, when the reduction value reaches 47% in PHFRM-0.75-0.25 and in average 26% in other fibers mortars.

3.2 Autogenous shrinkage

Autogenous shrinkage is the chemical shrinkage that presents the volume change occurring during hydration reactions, when water is mixed with cement without any humidity exchange with external environment. As observed in Fig. 10, the evolution of autogenous shrinkage continues until the first ten days and then stabilizes, which means that the stabilization of autogenous shrinkage takes place at very early ages, by comparison to total shrinkage. As noted in total shrinkage, the mixes containing more of coarser fibers (PF45) have presented the lowest values of autogenous shrinkage than those containing more of finer fibers (PF25). The Fig. 11 shows the evolution of autogenous shrinkage, with regard to total shrinkage; to estimate this evolution, the percentage (autogenous shrinkage / total shrinkage) is calculated for 7 days (see Fig. 11(a)) and 28 days (see Fig. 11(b)). The autogenous shrinkage represents only 39% of total shrinkage at 7 days and 61% at

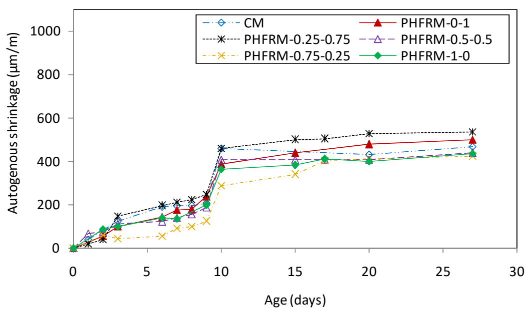
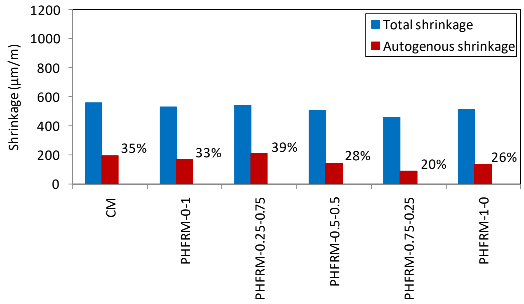
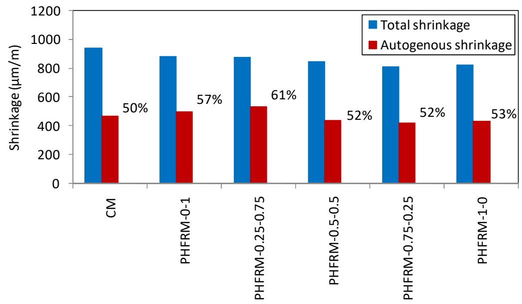


Fig. 10 Autogenous shrinkage development in different mortars



(a) At 07 days



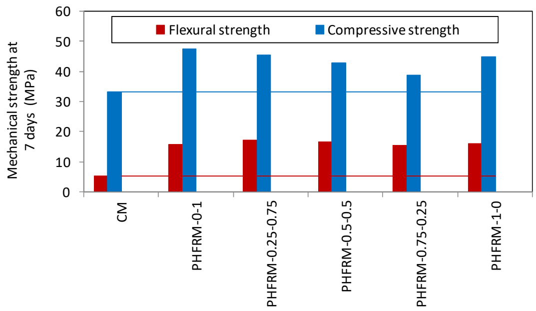
(b) At 28 days

Fig. 11 Evolution of autogenous shrinkage compared to total shrinkage

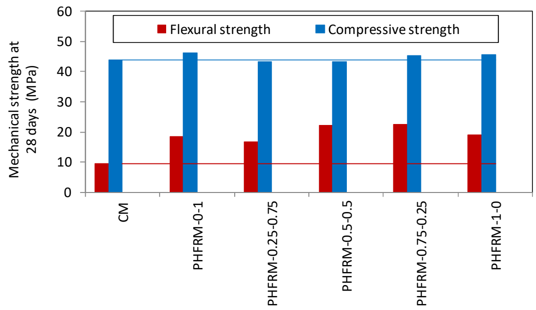
28 days; these percentages which are the higher values correspond to the fiber mortar PHFRM-0.25-0.75.

3.3 Strength properties

The mechanical strengths of tested mortars are schematized in Figs. 12(a)-(b) for 7 and 28 days, respectively. It is well observed that mixes containing polypropylene fibers produce a good flexural behavior, by comparison to the control mortar. Some authors (Eidan *et al*. 2021) have reported through their experimental investigation, that polypropylene fibers increase the strain of concrete at maximum load without affecting the ultimate failure load. The effect of used fibers on the flexural behavior is more appreciated at 7 days aging; the values of the flexural strength which are close in all fibers mortars exceed three times that of control mortar, while at the age of 28 days they are twice as high. The good contribution of PHF towards the flexural behavior can be attributed to the good bridging capacity of polypropylene fibers that ensures the transfer of the load from cracked matrix to fibers, just after cracking starts (see Fig. 13(a)) and also to fiber length (3 cm) that seems to be sufficient for ensuring a good attachment to the matrix. These results are in accordance with various literature findings (Langlois *et al*. 2007, Ramadoss and Ngamani 2008, Sun and Xu 2009, Mamlouk and Zaniewski 2011, Pereira de Oliveira and Castro-Gomes 2011, Alamshahi *et al*. 2012, Hosseini 2020). At 7 days of age, the augmentation of the flexural strength varies between 186% in PHFRM-0.75-0.25, 190% in PHFRM-0-1, 196% in PHFRM-1-0, 211% in PHFRM-0.5-0.5 and 220% in PHFRM-0.25-0.75, compared to control mortar. Nevertheless, at the age of 28 days, the effect of coarser fibers (PF45) on the flexural behavior is slightly more important than that of finer fibers (PF25), which is well demonstrated by the higher values of the flexural strength in PHFRM-0.5-0.5, PHFRM-0.75-0.25 and PHFRM-1-0, where the strength augmentation is about 136, 141 and 104%, respectively. As reported by many researchers (Akkaya *et al*. 2001, Ozyurt *et al*. 2007), the positive effect of coarser fibers (PF45) on the flexural behavior is probably due to their good dispersion in the matrix by comparison to finer fibers (PF25). Compared to PF25 fibers, PF45 fibers have showed a good distribution, because their specific surface is lower and their effect on the mortar workability is less important, so in this case the material still more workable, with less risk of formation of fiber balls, which facilities the movement of fibers and promotes their good dispersion. These findings can be also relied to the results of the shrinkage; the mortars presenting a good flexural behavior are the same that have produced the lowest shrinkage. The good dispersion of polypropylene fibers into the matrix increases the probability to have the maximum number of fibers in the cracking section,



(a) At 07 days



(b) At 28 days

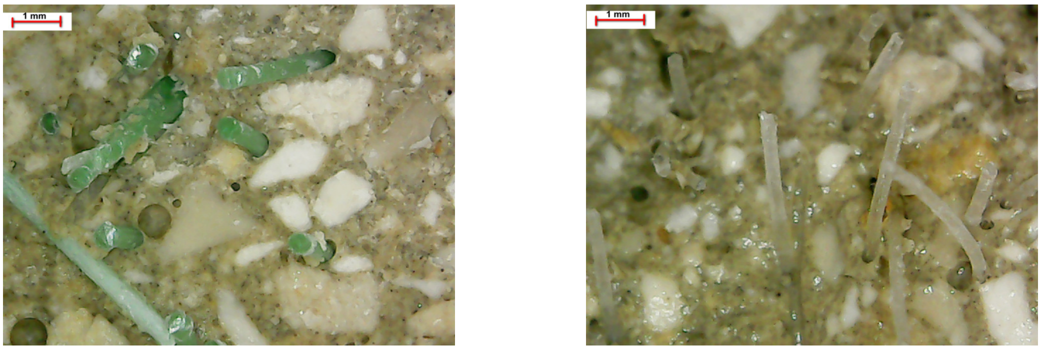
Fig. 12 Mechanical strength of different mortars

i.e., between cracks lips (see Fig. 13(b)). The presence of these efficiency fibers in the cracking section not only improves the tension behavior of the mortar, but also delays the appearance of cracks and prevents their opening. As showed in digital microscope images (see Figs. 14(a)-(b)), no fibers pullout is detected in all PHFRM, which confirmed once again the efficiency of used length (3 cm) of polypropylene fibers to ensure their anchoring into the matrix.

According to Figs. 12(a)-(b), the polypropylene fibers are more efficient in flexural behavior than in compressive behavior, as already confirmed by a previous work (Das *et al*. 2018). Like in the flexural behavior, the effect of polypropylene fibers is well observed on the compressive strength at 7 days; a considerable strength augmentation ranging from 17% in PHFRM-0.75-0.25, 29% in PHFRM-0.5-0.5, 36% in PHFRM-1-0, 37% in PHFRM-0.25-0.75 and 43% in PHFRM-0-1 is reached, comparing to control mortar. Nevertheless at 28 days, the augmentation percentage of the compressive strength does not exceed 5%. It is well known that the evolution of the compressive strength of concrete depends on the hydration evolution, which is in function of components, curing and conservation conditions; in this study all mortars had the same composition and were conserved in the same environment. But by comparison between Figs. 12(a) and 12(b), it can be seen that the use of PP fibers has participated to the rapid evolution of the compressive strength of mortar and after only seven days of age, the mortars have reached a high percentage of their strength at 28 days. Hussain *et al*. (2020) justified the smaller improvement in compressive strength of polypropylene fiber concrete by the lower compressive strength and elasticity modulus of this fiber, compared to that of steel and glass fibers. Generally, the obtained results seem very interesting when compared to those of the literature; because in most studies (Yap *et al*. 2013, Borg *et al*. 2016, Marthong 2019, Alwesabi *et al*. 2020, Alaskar *et al*. 2021), the reinforcement of materials by fibers did not expend

(a) Bridge effect of fibers (b) Failure section of fibers mortar

Fig. 13 Mortar under flexural load



(a) PHFRM-1-0 (b) PHFRM-0-1

Fig. 14 Digital microscope images of fibers mortar

a considerable effect on their compressive behavior if not negative effect. The fibers used in this investigation are polypropylene fibers which are characterized by their lightness and high flexibility, compared to other types of fibers, even those of a synthetic nature. So due to these properties, the used fibers can easily arrange themselves into the matrix during mixing and casting, without hindering the compactness of the material, thereby maintaining its good compressive strength. Basing on the experimental results it is also remarked that the density of both control mortal and polypropylene fiber reinforced mortars is close; it varies between 2.1 for control mortal, 2.07 for PHFRM-1-0 and 2.11 for PHFRM-0-1. This conclusion confirmed once again the positive effect of polypropylene fiber on the compressive behavior of the mortar.

4. Conclusions

In the present study, the effect of polypropylene hybrid fibers PHF on shrinkage and mechanical performances of mortar is investigated. From the experimental results, the following conclusions are drawn:

- The workability of mortars is negatively affected by the addition of polypropylene fibers, in both single and hybrid form.

- Compared to control mortar, the addition of PP fibers in both single and hybrid form decreases the total shrinkage. Coarser fibers (PF45) are most effective for reducing shrinkage risk.
- The mixes containing more of coarser fibers (PF45) have presented the lowest values of autogenous shrinkage than those containing more of finer fibers (PF25).
- The presence of single or hybrid polypropylene fibers enhances the flexural behavior of mortar and their effect on the compressive behavior is less important.
- Compared to control mortar, the fracture in PHFRM is slower and the distribution of cracks is better.

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