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Physical-mechanical Evaluation of Polyethylene Terephthalate Fiber Dune Sand Mortar Exposed to Elevated Temperature

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Abstract

The mechanical properties of mortar containing Polyethylene Terephthalate (PET) as Strapping Band Fibers (SBF) replacing natural sand have been studied by many researchers. These studies indicate that when SBF is used as a substitute for sand in mortar, the characteristics in both the fresh and hardened states are altered. This experiment's purpose is to valorize local materials, which are abundant in the region of Djelfa (Algeria), in cement mortar manufacturing and to discuss the influence of these materials on the mechanical and physical characteristics of the resulting mortar at the room, and at the high temperature. This study presents the results of an experimental investigation into the effects of high temperatures on the properties of dune sand mortar made with strapping band fibers. The method for formulating the mortar mixes was based on the progressive replacement of dune sand by PET fibers, with weight contents of 0%, 0.5%, 1%, 1.5%, 2%, and 2.5%. Several tests have been carried out to study the evolution of the different characteristics of mortar mixtures. The workability, bulk density, compressive and tensile strengths, and all samples were subjected to temperatures of ambient, 100 °C, 200 °C, and 400 °C. The results demonstrate that the inclusion of the recycled fibers and the preservation mode had remarkable effects on the characteristics of the mortar obtained.

Keywords: dune sand, mortar, elevated temperature, mechanical strength

1 Introduction

The process of valorizing local and waste materials in mortar production is among the most effective ways to solve the issue of a lack of sources of building materials and pollution in urban and rural areas. The use of Polyethylene Terephthalate band fibers as incorporation into dune sand mortar not only contributes to the exploitation of worn strapping bands, but it can also have a positive role in improving the performance of mortar.

Many investigations have been conducted on this topic. The results of the experiments showed that the incorporation of PET as a fiber, bond, or aggregate could have a significant influence

on cementitious materials' properties, mechanical strength, deformability, and durability [1-9]. According to Hacini et al. [1], the use of PET aggregates as a replacement for natural sand allows reducing the density of reinforced mortars. Umasabor et al. [2] investigated the effects of using PET as an additive on the mechanical strength of concrete and reported that there was a progressive decrease in the flexural strength of the concrete as the PET content increased in the concrete. Martinez-Barrera et al. [3], Meza de Luna et al. [4], and Kutum et al. [5] concluded that the size and concentration of PET flakes had a significant impact on the compressive strength of concrete. The results obtained by Singh et al. [6] showed that the addition of PET waste to concrete as a fine aggregate replacement increased the mechanical strength of the concrete. On the other hand, Lin et al. [7] and Uddin et al. [8] reported that the use of PET fiber reinforcement enhances the interfacial properties between fiber and matrix. Alaloul et al. [9] studied the effects of PET and polyurethane (PU) on the mechanical and thermal properties of interlocking bricks, and they reported that adding PET and PU improved the impact strength.

The use of PET as mechanical reinforcement in concrete and as an enhancement in elasticity for concrete structures would not only assist in addressing the issue of environmental impact, but it could also have a positive and significant effect on the ductility behavior of beam structures and improve the electrochemical properties of reinforcing steel in concrete. [10-12]. The use of PET-FRP (Fiber Reinforced Polymer) in the production of reinforced concrete (RC) structures is a relatively recent technique. The use of PET fiber concrete with FRP reinforcement systems and techniques to retrofit RC structures has significantly increased the ultimate load, giving PET-FRP a great advantage over conventional materials. [13,14].

Mohammad et al. [15] studied the impact of the partial replacement of natural aggregates by recycled fine PET aggregates. Various incorporations of PET fine aggregates ranging from 10 to 50% were used in concrete. The optimum percentage of admixture was found to be 10% of PET, which improved the qualities of fresh and hardened concrete.

Ayush et al. [16] replaced recycled Polyethylene Terephthalate fiber in the concrete with fine aggregate and investigated workability, and mechanical properties. Their study concluded that plastics can be used in concrete up to 3% as a partial substitution for fine aggregate, as they reduce workability, increase compressive strength, and also decrease concrete density.

Haikuan et al. recently investigated the erosion resistance of normal concrete (NC) and recycled plastic concrete (RPC) in a solution of sodium sulfate at concentrations of 3%, 5%, and 7% [17]. According to the results, as the erosion concentration and time increase, the mass increase rate of RPC and NC also increases. Under 3% and 5% concentration erosion, the compressive strength increases and then decreases as the rate of mass changes and the speed of the ultrasonic waves' velocity changes.

On the other hand, PET-modified concrete is appropriate for structural uses due to its acceptable fresh, mechanical, microstructural, and thermal properties [18,19]. This study examines the compressive strength and flexural strength of dune sand (DS) mortar that contains varying amounts of PET strapping band fibers that have been exposed to elevated temperatures. The performance of the reinforced dune sand mortar was compared to that of an alluvial sand (AS) mixture and a DS-based mortar without fiber (the control mix).

The main objective of the experimental work presented in this paper is to examine the possibility of applying mortar containing dune sand and PET scrap waste fiber for building construction. This experimental study also looked at the effects of using PET Strapping Band Fibers (SBF) at progressive levels (0%, 0.5%, 1.0%, 1.5%, 2.0%, and 2.5% by weight) on the physical and mechanical characteristics of the obtained mortar at ambient and elevated temperatures.

2 Experimental Program

2.1 Materials

The type of cement used in the present study was Composite Portland Cement (CEM II/A 42.5) brought from the BISKRIA CEMENT factory, Biskra (Algeria). The cement used has a bulk and a specific gravity of 1.96 g/cm^3, and 3.11 g/cm^3, respectively, and Blaine fineness of 3225 cm^2/g.
In the present research, two different sorts of sand have been employed; dune sand, denoted by (DS), and alluvial sand denoted by (AS). These sands are from the Djelfa region (Algeria). The physical specifications of each sand are given in Table 1. DS and AS sands have grain sizes of 0/0.315 mm and 0/4 mm, respectively (Figure 1). The X-ray diffraction (XRD) analysis shows the presence of SiO_2 (Quartz) as the main component, which indicates the siliceous nature of the sands used (Figure 2).

Table 1: Physical properties of the sands used

Property	**AS**	**DS**
Apparent density (g/cm^3)	1.61	1.46
Specific gravity (g/cm^3)	2.60	2.53
Total porosity (%)	38	43
Compactness (%)	62	57
Water absorption capacity (%)	0.87	2.35
Visual sand equivalent (%)	81	79
Sand equivalent with the piston (%)	80	75
Fineness modulus	2.36	0.86

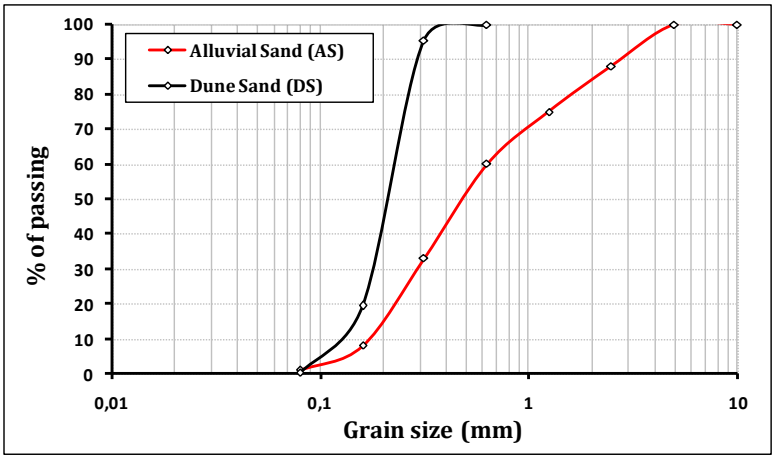


Figure 1: Particle size distribution of the sands studied

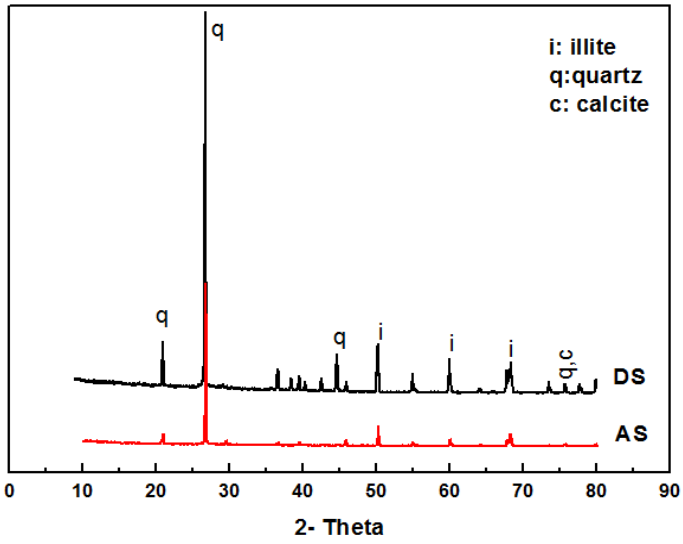


Figure 2: X-ray diffraction patterns of sands used

Polyethylene terephthalate (PET) waste used in this study has a tensile strength of up to 36 MPa, a melting point of 255-265°C, and a range of glass transition temperatures between 70°C and 80°C. The used Polyethylene Terephthalate fibers, designated by (F), were obtained manually by cutting packaging straps. Their dimensions are between 15 and 20 mm in length, 1.0 and 1.5 mm in width, and 0.55 mm in thickness. The fibers used have a density of 1.29. Figure 3 shows a sample of the PET fibers used.



Figure 3: PET strap waste fibers used

2.2 Mix Proportions and Sample Preparation

The experimental procedures applied in this work to determine the mechanical resistance employed prism samples measuring 4×4×16 cm^3. Dune sand mortar mixtures with various amounts of PET-SBF fibers were prepared and performed according to the NF EN 196-1 standard (Table 2). In order to assess the impact of fiber inclusion on the different physical and strength characteristics of the mortar, the dune sand was substituted by 0%, 0.5%, 1.0%, 1.5%, 2.0%, and 2.5% PET fibers.

Table 2: Mix composition of designed mortars

Mixture	Composition	Cement (g)	DS (g)	AS (g)	F (g)	W/C
M_{AS}	100% AS	450	-	1350	0	0.7
M_{DS}	100% DS	450	1350	-	0	0.7
M_1	84.5% DS + 0.5% F	450	1343.3	-	6.7	0.7
M_2	84% DS + 1% F	450	1336.5	-	13.5	0.7
M_3	83.5% DS + 1.5% F	450	1329.8	-	20.2	0.7
M_4	83% DS + 2% F	450	1323	-	27	0.7
M_5	82.5% DS + 2.5% F	450	1316.3	-	33.7	0.7

After mixing is complete, the fresh mixtures were molded, and they were then subjected to 20 to 30 seconds of vibration on a vibrating table. During the first 24 h, the samples were stored in ambient laboratory conditions of temperature (23 ± 2°C) and relative humidity (50% ± 10%). They were then demolded and kept submerged in drinking water until the test day.

2.3 Testing Procedures and Heat Treatment Process

For fresh mortar, the workability was determined using an LCPC mortar maniabilimeter, (NF P18-452 standard). The experiment consists of determining the consistency of a fresh mortar subjected to specified vibrations. For hardened mortar samples, the mechanical characteristics were evaluated at 28 days before and after the heat treatment process, using mortar prism samples of 4×4×16 cm^3 in dimension (NF EN 196-1 standard). The three-point bending test was used to assess the flexural strength. After that, the half-samples resulting from the flexural test were tested in axial compression. The water absorption capacity and apparent density of mortar in the hardened state were investigated according to the European standards NF EN 1015-18 and NF EN 1015-10 respectively.

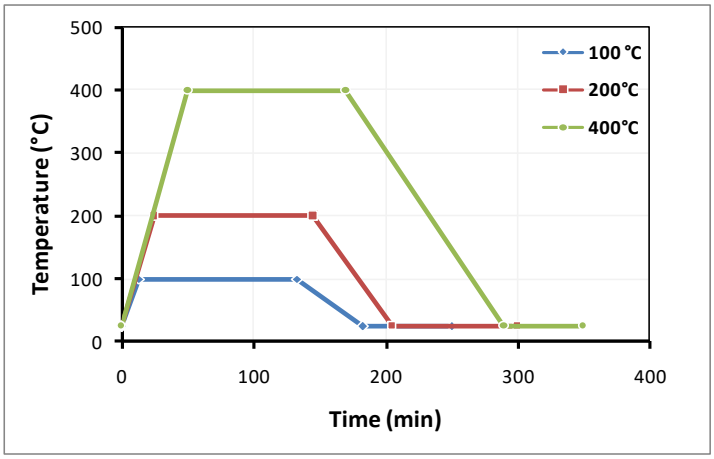


Figure 4: Heat treatment process diagram

To evaluate the effect of elevated temperature on the mechanical characteristics of the mortar studied, the samples were heated in an electric furnace laboratory (FOURS ME brand) for 2 hours at temperatures of 100 °C, 200 °C, and 400 °C, with an increment rate of 7.84 °C per minute (Figure 4). After that, the samples were allowed to cool to room temperature (23 ± 2 °C). It should be noted that when raising the temperature from 200°C to 400°C, we observed the melting of the PET fibers appearing on the faces of the samples. Figure 5 illustrates the state of the mixture M_2 when the temperature reaches 200°C and 400°C.

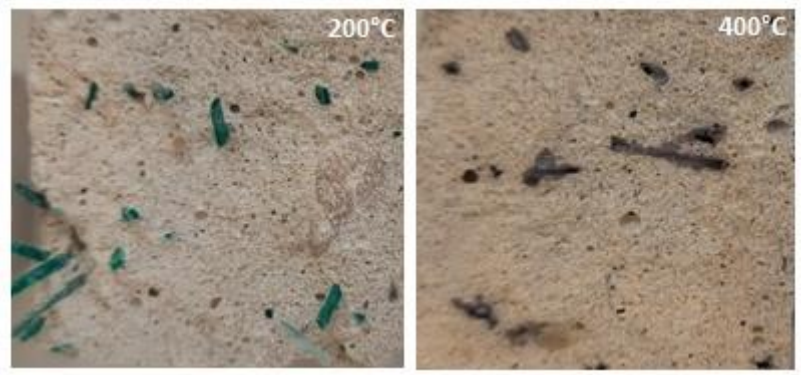


Figure 5: The visual state of the mortar M2 at a temperature of 200°C and 400°C

3 Results and Discussion

3.1 Consistency of Fresh Mortar

The results of the flow time of PET fiber-reinforced mortar mixtures with different fiber contents are plotted in Figure 6. The results of this experiment showed that the incorporation of PET fibers with substitution rates less than or equal to 1.5% does not have a substantial impact on the consistency of the mixes; the consistency shows a constant value (4 seconds) for 0%, 0.5%, 1%, and 1.5% PET fibers. On the other hand, it is found that beyond 1.5%, the flow time decreases progressively with the number of fibers added, to reach a minimum value (one second) for 2.5% of PET fibers. The substitution of 2.5% dune sand with PET waste fibers makes it possible to achieve consistencies equal to those of alluvial sand mortar (MAS); which shows that the incorporation of 2.5% fibers results in a considerable increase in workability.

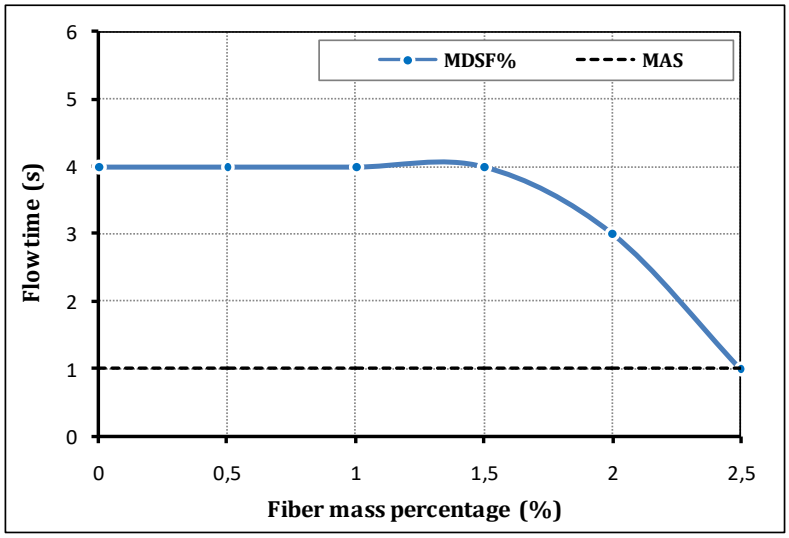


Figure 6: Evolution of the consistency as a function of PET fibers amount

The increase in consistency may be attributed to the distinction in water absorption capacity between DS and fibers, which increased the amount of excess water and therefore the workability. The decrease in flow time is also attributed to the longitudinal shape of PET waste fibers, which assist the mixed particles to flow over each other [20].

3.2 Bulk Density of a Hardened Mortar

The results presented graphically in Figure 7 show that at room temperature, the inclusion of recycled fibers results in a significant enhancement in bulk density for a reinforcement rate of 0.5% (the case of the mixture M_1). This replacement ratio allows for a bulk density comparable to that of alluvial sand mortar (1.98 g/cm^3). Beyond this percentage, a general decrease in apparent density was observed. The mortar specimens with recycled fibers exhibited apparent densities varying from 1.95 to 1.79 g/cm^3 at room temperature. The reinforcement of dune sand mortar with 1%, 1.5%, 2%, and 2.5% PET strap waste fibers induces reductions of 0.5%, 2.1%, 1.6%, and 5.8%, respectively, in comparison to a mortar without fibers. This might be related

to PET fibers' specific gravities which are relatively low compared to those of dune sand (1.29 and 2.53, respectively).

The findings demonstrate that the exposure of the investigated mortar specimens to high temperatures has an important effect on the bulk density; for 0%, 0.5%, 1%, 1.5%, and 2% of PET fibers, the increase in temperature significantly decreases this characteristic. For 0.5% of fibers, treatment of the mortar samples at temperatures of 100°C, 200°C, and 400°C causes reductions of 3.6%, 5.1%, and 5.6%, respectively, in comparison to the bulk density at room temperature.

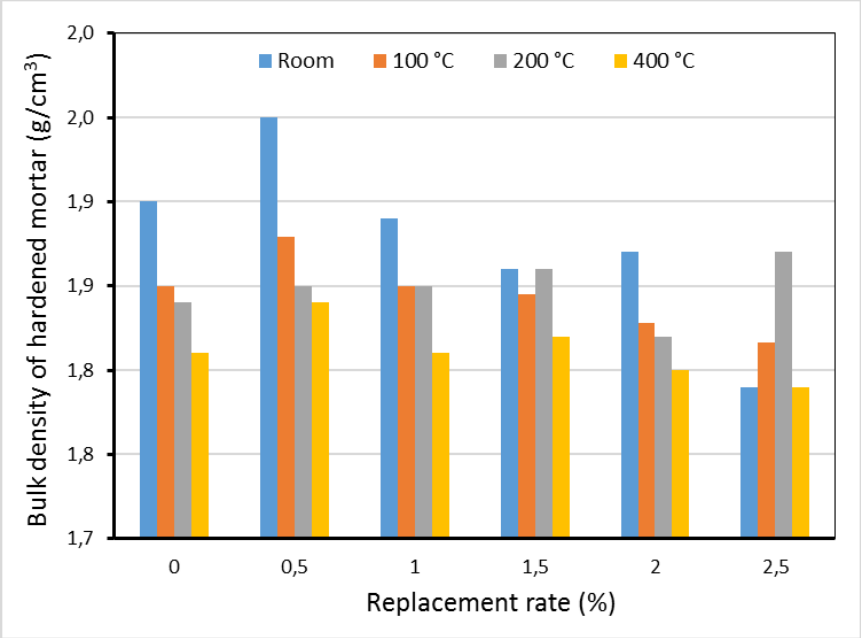


Figure 7: The influence of replacement rate on mortar dry bulk density at room and high temperatures

These results coincide with those obtained by other authors who have studied the thermo-mechanical characteristics of mortars containing expanded vermiculite powder at high temperatures [21]. On the other hand, for 2.5% fibers, we notice improvements of 1.5% and 4.5% for 100°C and 200°C, respectively.

3.3 Water Absorption at Room Temperature

Figure 8 illustrates the impact of the fiber ratio on the water absorption of dune sand mortar. From the results obtained, it should be noted that the reinforcement of the DS-mortar by the introduction of PET fibers results in a continuous increase in the water absorption capacity, which shows that these fibers do not participate in improving the compactness of mortar mixes.

The samples of the dune sand mortar with PET fibers exhibited water absorption capacities varying from 11% to 15.5%. The minimum value of water absorption capacity (11%) was observed at 0% and 0.5% replacement levels. The maximum value is given by the mixture containing 2.5% PET fibers (mixture M_5); the incorporation of PET fibers can generate an important increase in water absorption of the order of 40% in comparison to the mortar without

fibers. The reinforcement of dune sand mortar with PET strap waste fibers does not allow obtaining water absorption values close to those of the SA-based mortar (MSA); this might be attributed to the AS sand's better particle size distribution as compared to the DS sand.

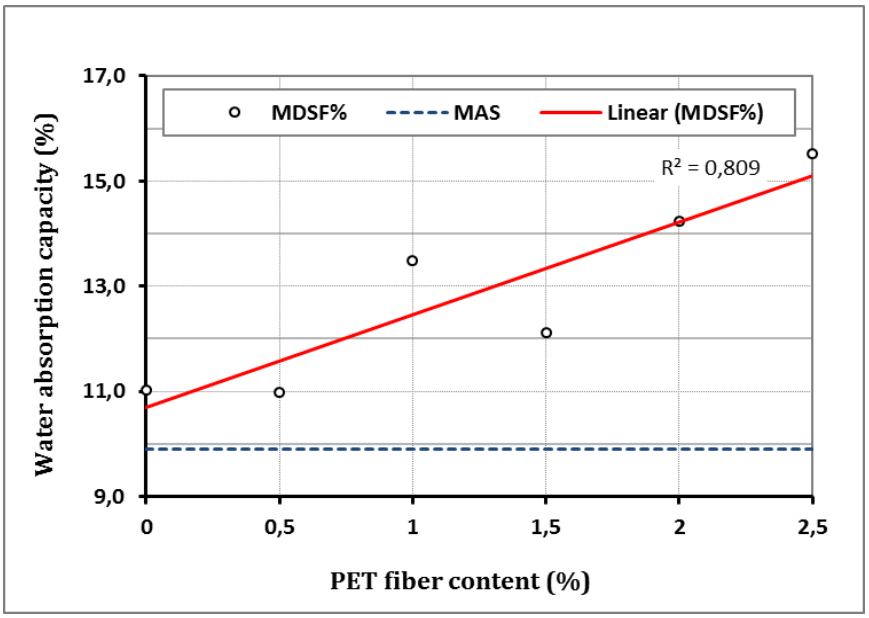


Figure 8: Impact of the PET replacement ratio on the water absorption capacity

3.4 Compressive Strength of Hardened Mortar

Figure 9a depicts the results of the compressive strength test on mortar specimens after exposure to temperatures ranging from room temperature to 400 °C. Figure 9b depicts the changes in compressive strength at temperatures of 100 °C, 200 °C, and 400 °C. As it appears, the mortar samples treated with recycled fibers developed compressive strengths ranging from 17.8 to 21.2 MPa at room temperature. Under these storage conditions, the fiber reinforcement of the dune sand mortar does not make it possible to give higher resistances than that of the AS-based mortar (MAS). of 21.2 MPa was achieved for a replacement rate of 2% (an improvement of 10.4%), and the minimum value of 17.8 MPa was noted for the mortar containing 1% PET fibers, i.e., a reduction of 7.3% in comparison with the control mortar (MDS). The factors that lead to a decrease in compressive strength were principally attributed to the increase in porosity and decrease in bulk density with increasing replacement ratio.

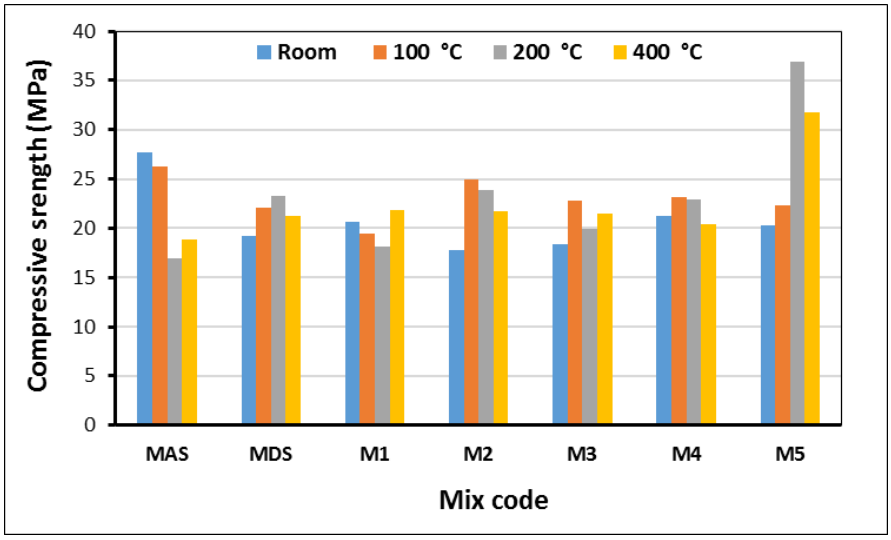


Figure 9a: Evolution of compressive strength as a function of the heating temperature

The inclusion of recycled fibers improved the mechanical performance of the reinforced mortar at 100°C, 200°C, and 400°C. At 100 °C, the incorporation of 1%, 1.5%, 2%, and 2.5% PET fibers showed good performance with improvements in compressive strengths of 40%, 24%, 9%, and 10%, respectively, as compared to the control mortar (MDS). However, a reduction in strength of 6% was recorded at 0.5% of fibers. The improvement in compressive strength can be attributed to reactions that occur during the heating process. [22]. At 200 °C, a very high compressive strength enhancement (82%) was recorded at a replacement rate of 2.5%. However, at 0.5% PET fibers, there is still a strength reduction of 6%; it seems that the behavior of the fibers is better when they overlap or intersect than when they are isolated.

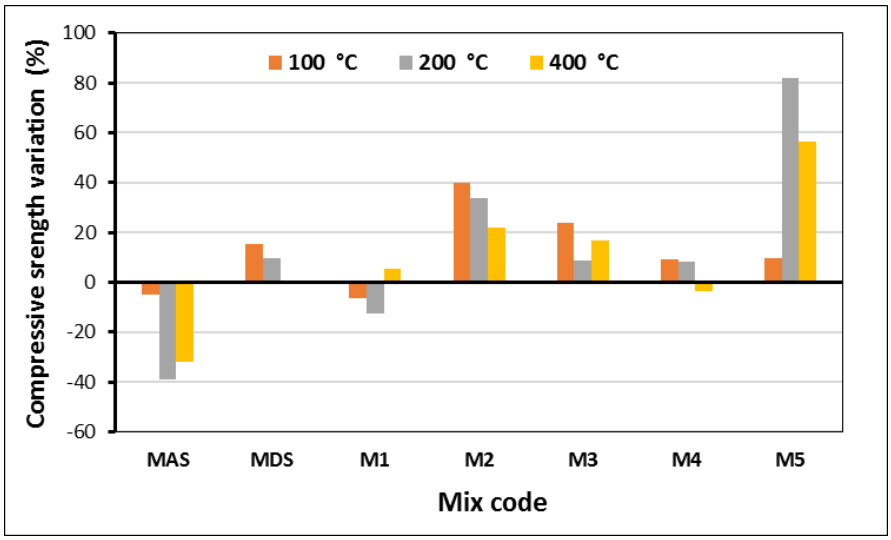


Figure 9b: Influence of heating temperature on compressive strength variations

At 400 °C, improvements in compressive strength were observed for fiber contents of 0.5%, 1%, 1.5%, and 2.5%. The results also show that adding 2.5% PET fibers to dunes sand mortar results in the highest compressive strength. It is also noted that the DS-based mortars, with or without PET fibers, exhibit better high-temperature resistance performance than AS-based

mortar; it appears that the illite of DS is a refractory or heat-resistant component that contributes to this enhancement at high temperatures. The AS-based mortar exhibited compressive strength reductions of 5.1%, 39.1%, and 32.1% at 100°C, 200°C, and 400°C temperatures, respectively.

3.5 Flexural Strength of Hardened Mortar

Figure 10a shows the experimental results obtained from the bending test of the samples studied after being subjected to heating temperatures ranging from room temperature to 400 °C. Figure 10b illustrates the improvements and losses in flexural strength values at different temperatures. As shown, the dune sand mortars reinforced with PET strap waste fibers exhibited bending strengths ranging from 1.23 to 1.72 MPa at ambient temperature. Similar to the results for compressive strength, the use of PET waste fibers as mortar reinforcement does not make it possible to achieve higher flexural strengths than that of the AS-based mortar. The greatest value (1.72 MPa) was achieved for 0.5% PET fiber (an improvement of 11%). The significant gain in strength is the result of the bonding force between the fibers and the mortar matrix. In comparison to the control mortar (MDS), the bending strength decreased by 20.6%, reaching its lowest value of 1.23 MPa. This reduction in strength is mainly related to the decrease in compactness with increasing fiber content; the water absorption values (Figure 8) show the impact of PET fiber inclusion on compactness.

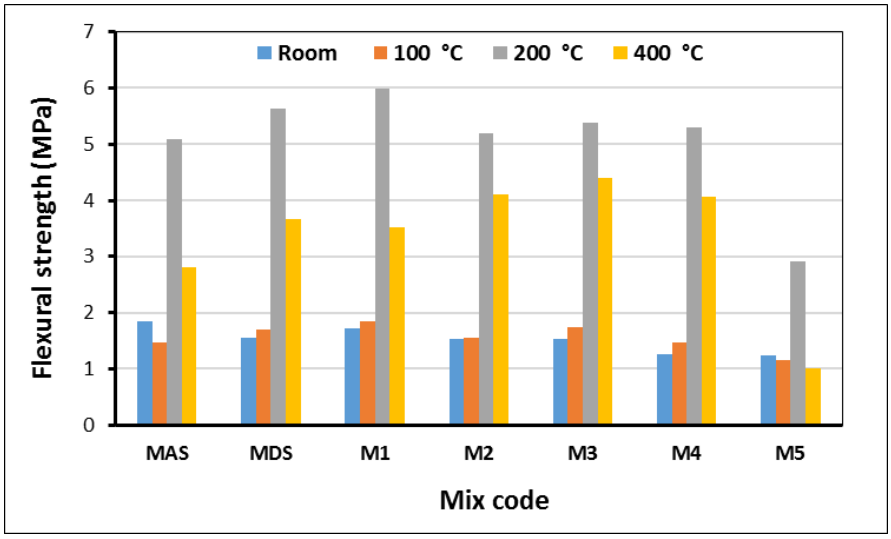


Figure 10a: Effect of temperatures rate on flexural strength

At 100°C and 200°C, the best flexural strength results were obtained for the fiber content of 0.5%; the improvements recorded for this replacement rate are respectively 8.9% and 6% in comparison to the DS-based mortar without fiber (MDS). For mortar specimens heated at 400 °C, a decrease in flexural strength was noticed compared to those heated at 200 °C. These samples exhibited strength reductions of 44.7%, 35.1%, 41.3%, 21.0%, 18.3%, 23.4%, and 65.7% for MSA, MSD, M1, M2, M3, M4, and M5, respectively. These important reductions may be associated with the cracking in the mortar matrix and with the voids created after the melting of the PET fibers. Also, this would coincide with the melting temperature of the fibers (Figure 11). It is also noted that the mortar with 2.5% PET fibers (M5) has the lowest flexural

strength values when compared to other mixes; this is primarily due to the high content fiber, which reduces adhesion between fiber and matrix, resulting in poor tensile stress transfer.

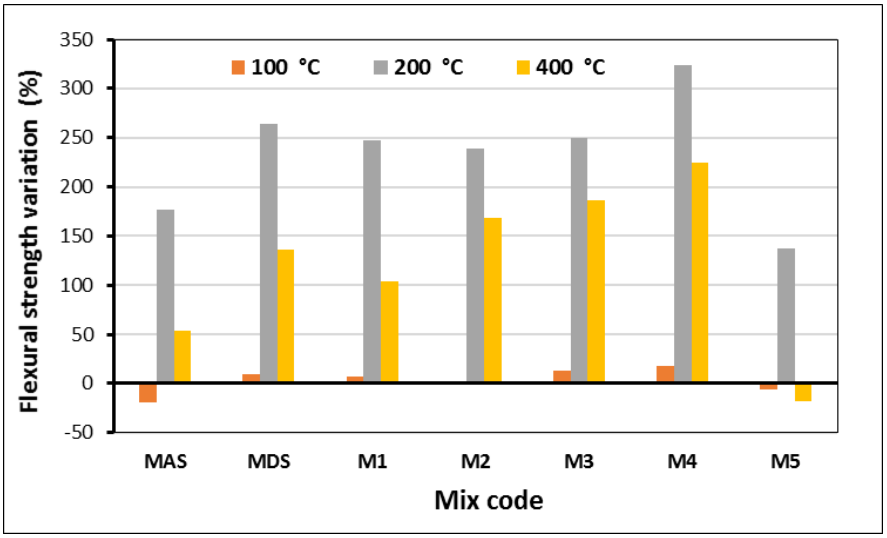


Figure 10b: Effect of temperatures rate on flexural strength variations



Figure 11: Formation of voids in the M5 mortar matrix after heating at 400 °C

4 Conclusions

Many experiments on PET fiber-reinforced dune sand mortar have been conducted. According to the findings of this study, adding recycled PET fiber to mortar had a significant impact on the physical and mechanical characteristics of the mortar obtained in both fresh and hardened states.

The research's conclusions may be summarized as follows:
• The incorporation of PET fiber with replacement rates less than or equal to 1.5%, has little impact on the mortar consistency. However, beyond 1.5% the flow time decreases with the percentage of fibers until it reaches the lowest value (at 2.5% of PET).

• The inclusion of 0.5% PET waste fibers results in a significant increase in bulk density at room temperature. After this percentage, a general decrease in apparent density was observed.

• The use of PET strap waste fibers improves the behavior of reinforced dune sand mortar at 100°C, 200 °C, and 400°C. Compared to AS-based mortars, DS-based mortars have much higher mechanical performance at high temperatures.

• The best flexural strength results measured after heating at 100 °C and 200 °C were obtained for 0.5% fiber. For mortar samples exposed to 400 °C, a decrease in flexural strength is observed compared to samples exposed to 200 °C.

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