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Assessment of mechanical and durability properties of HPC used for tunnels at different temperatures

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ABSTRACT

This work presents the mechanical and durability evaluation of high-performance concrete mixes used for tunnels after exposure to different temperatures. Nine HPC mixes were investigated. The first group has W/C ratios; of 0.25, 0.31, and 0.37. The second group has silica fume addition by about 5.0%, 10%, and 15% of cement weight. In the third group, polypropylene fibers were added to the concrete by the ratios of 0.211% from the concrete volume. The mechanical properties were measured at room temperature and after exposure to temperatures 400°C and 800°C for curing periods of 28 and 56 days. The durability was evaluated by water penetration depth at room temperature. Scanning electron microscopes were also carried out. The results indicate that at a temperature of 400°C, the compressive strength of the concrete increased. They decreased with further increases in temperature over 400°C to 800°C. At 400°C, the highest compressive strength improvement is achieved by about 18.2% after 56 days of curing in the case of 10% SF The addition of 0.211 polypropylene fibers significantly increased the compressive strength after curing for 56 days by about 32.1%. Moreover, at 800°C, the highest tensile strength improvement achieves by about 87.5% after curing for 56 days in the case of SF=10%. The lowest porous penetration depth of water was found for a mix containing W/(C+SF) = 0.37, silica fume =10%, and polypropylene fibers =0.211%.

1. Introduction

One of the most important factors affecting the structural integrity of concrete structures is fire because of its negative impact on the building's physical properties, strength, and function. Therefore, it is important to predict the behavior of concrete when exposed to high temperatures to evaluate the integrity of the concrete structures [1, 2].

During the last few years, researchers have tended to study many properties of high-performance concrete because of the many advantages of these kinds of concrete, so for the construction of high-rise buildings, tunnels, and concrete structures that need durability compared to conventional concrete. HPC mixes have low permeability using the lower water -

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cementations, produced with partial replacement of cement with additives [3-6].

Chowdhury et al. [7] present a study to determine the effect of high temperatures of 60, 75, 100, 200, 400, and 600°C with exposure to variable periods 4, 8, 12, 72 hrs. and one month for mixes of high strength concrete. Studying the effect of silica fume on permeability implemented by Chaudhary and Sinha [8] indicated that the water permeability test result reveals about 87 % reduction in the permeability coefficient achieved by the inclusion of 10% silica fume by weight of cement. The results concluded a remarkable decrease in chloride ions penetration due to silica fume inclusion.

Khodja and Hadjab [2] present an experimental study on the performance of concrete exposed to high temperatures. The evaluation was done using two mixtures: Normal concrete and high-performance concrete, replaced with 10% silica fume by weight of cement and 1.5% superplasticizer. The strength of concrete mixes decreased with increasing exposure temperature, reaching about a quarter of its initial strength at 900°C. Moreover, the SEM test displayed that the high temperature caused weak adhesion of the aggregate and the mortar due to the appearance of cracks.

Another study about the effect of high temperature on the mechanical properties, including compressive, tensile, shear strength and durability, was evaluated based on the surface water absorption, water penetration depth, and weight loss tests by Abdi Moghadam and Izadifard [9].The results showed that the high temperature decreased the mechanical properties of concrete, which increases with temperature, then decreases with another temperature. In comparison, the cement replacement of silica fume improved the compression and tensile strength in the range of 1.35-26.74% and 0.37-234.58% at the tested temperatures. On the other hand, a lot of research focused on adding fibers to concrete which has a remarkably favorable effect on the mechanical properties of the concrete [10, 11].

Shariq et al. investigated the effect of high temperature on the tensile strengths of normal and high-strength concrete with and without polypropylene fibers. The results indicated that the high-temperature effect is the highest at flexural strength. At the same time, polypropylene fibers displayed increased ductility, fire resistance, and tensile strength [12]. In previous studies, such as the study Sharaky et al. [13], showed the effect of HSC incorporating fumed silica and nano-silica exposed to elevated temperatures are evaluated as well as mass loss. The results concluded that concrete mixes containing NS, compressive strength remarkable increasing as the temperature was raised to 400 °C and decreased as the temperature increased from 400 to 800 °C. In addition, there is a noteworthy reduction in the tensile strength of concrete at T = 800 °C and 1000 °C. Shah et al. [14] their study showed that the mechanical properties of normal-strength concrete decrease at a 10% to 20% higher rate than high-strength concrete ranging between temperature and approximately 350°C, depending on the mix proportions and initial compressive strength of the concrete. The differences become narrower at a temperature above 350°C.

This work is focused on the effect of the high temperature on the mechanical properties of HPC mixes after curing periods of 28 days and 56 days. The influence of water-cementitious ratio, W/(C+SF), silica fume contents, and polypropylene fibers were studied by measuring compressive and splitting tensile strengths, and permeability at room temperature, after being subjected to temperatures of 400°C and 800°C. Also, scanning electron microscope (SEM) results were analyzed.

2. Experimental Work

The experimental program of nine HPC mixes was investigated, where the first group had different W/C ratios; 0.25, 0.31, and 0.37The second group of HPC mixes are with silica fume addition of 5.0%, 10%, and 15% weight of cement to the mixtures of the W/(C+F) = 0.31. In the last one, the PP fibers were added to concrete mixes by the ratios of 0.211% from the concrete volume. All HPC mixes were tested at RT after exposure to 400°C and 800°C during curing periods of 28 and 56 days. Table 1 gives the proportions of each concrete mix in this study.

2.1. Material Properties

Ordinary Portland cement (CEM III 42.5 N) with a specific gravity of 3.15 was used in mixes for this work. The dolomite with maximum aggregate size of 19 mm and specific gravity of 2.6 was used as coarse aggregate. The fine aggregate was natural sand with a fineness modulus of 2.2 and specific gravity of 2.64 g/cm^3. Fig. 1 (a and b) shows grading curves of

coarse and fine aggregates confirmed with specification limits BS.882 [15]. The chemical compositions of cement and SF are typically used in [17]. The MasterGlenium ACE 3383 superplasticizer was used for the water-reducing ratio. The tap water was used as mixing water.

2.2. Mixtures preparation

The compositions of the control HPC mix used in this work were as follows: for 1.0 m^3 by kg, the cement was 470 kg, the water was 188.5 lit, the fine aggregate (sand) was 695 kg, the coarse aggregate (dolomite) was 955 kg, silica fume was 40 kg, PP fiber was 2 kg, and super plasticizer was six lit. The fresh concrete was cast in the prepared forms after the mixing process was complete. The cubic specimens of 100 × 100 × 100 mm and cylindrical specimens of 100 × 200 mm were cast for compression and tensile tests. The specimens were stored at room temperature for 24 hours and, after that, cured for 28 days and 56 days in the water tank. Fig.2 presents the specimen preparation stages in this work.

2.3. Test setup

The test setup is given in the following section. The compression and indirect tensile tests were performed by a compression testing machine of 2500 kN capacity at the materials lab of the faculty of engineering at Zagazig university according to EC203-2016 [16], as shown in Fig 3. with an accuracy of 5 KN Three specimens were averaged for each mix.The heating oven of 1200°C, also located at the materials lab of the engineering faculty at Zagazig University, was used to burn specimens at temperatures of 400°C and 800°C. The permeability test is important, especially for high-performance concrete that indicates durability and internal pore to structure. The details of this test can be seen in Fig 4. The SEM test was completed through standard steps at Mansoura University.

3. Experimental Results and Discussion

The experimental results of compressive and indirect tensile strengths at 28 and 56 days are given in Table 2. The data are given for room temperature, 400 °C, and 800°C.

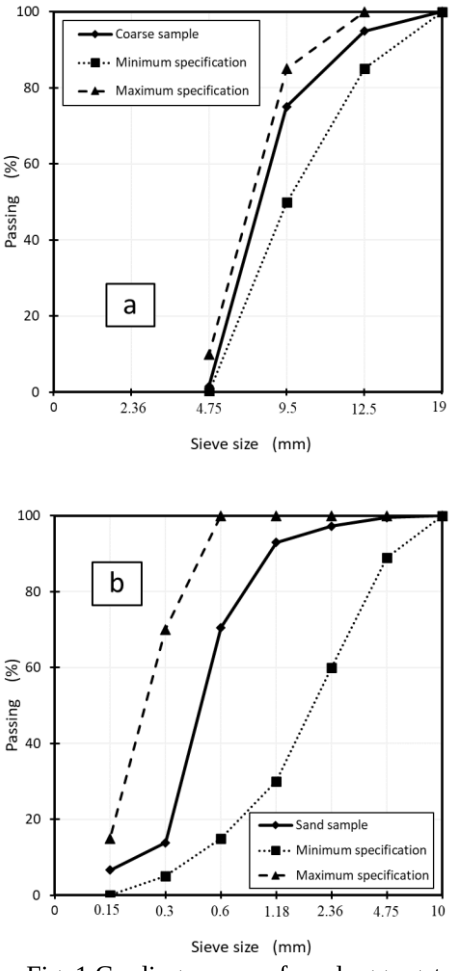


Fig. 1 Grading curves of used aggregates

3.1. The behavior of compressive strength at different temperatures

Fig. 5 shows 28 days of compressive strength for mixes M1, M2, and M3, at room temperature, 400 °C, and 800 °C. From the data shown in the figure, we can notice that at room temperature, the mix M2 with W/C = 0.31 records the highest value of compressive strength as compared to M1 and M3. As these mixes were exposed to a temperature of 400 °C, we can notice that the mix M1 with W/C = 0.25 gives the highest value of compressive strength by about 8.0% and 15% as compared to M2 and M3. On the other hand, when these mixes were exposed to a temperature of 800 °C, the results indicated that the mix M2 with W/ C = 0.31 gives the highest value of compressive strength by about 30.4% and 44.4 % as compared to M1 and M3.

Table 1: Concrete mixtures proportions

Mix ID	W / (C+SF)	Silica Fume, SF	Polypropylene fibers, PP	Superplasticizer %
M1	0.25	-	-	2.5%
M2	0.31	-	-	2.6%
M3	0.37	-	-	1%
M2S1	0.31	5%	-	1.1%
M2S2	0.31	10%	-	1.1%
M2S3	0.31	15%	-	1.1%
M1S1P	0.25	5%	0.211	2.29%
M2S2P	0.31	10%	0.211	2.2%
M3S3P	0.37	15%	0.211	2.2%

(a) (b) (c)

Fig. 2 Specimens preparation stage, (a) Mixing, (b) Cast and compaction, (c) Curing,

Fig. 3 Compression testing machine

Fig. 4 Water penetration test of concrete

Table 2 Compressive and tensile strength results of the tested mixes at 28 and 56 days

Mix ID	Compressive strength results					
	At 28days (MPa)			*At 56days* (MPa)		
	RT	400°C	800°C	RT	400°C	800°C
M1	48.3	63.4	27.9	-	-	-
M2	52.6	58.7	36.4	-	-	-
M3	45.1	55.1	25.2	-	-	-
M2S1	49.1	56.5	36.1	54.3	59.0	38.8
M2S2	56.6	67.7	41.8	63.1	69.4	47.8
M2S3	53.2	54.9	20.2	54.0	60.7	28.9
M1S3P	38.8	63.6	31.1	41.5	68.7	33.6
M2S1P	70.1	74.3	36.3	74.3	75	45.4
M3S2P	60.7	69.4	38.6	69.6	72.8	39.7
Mix ID	Splitting strength results					
	At 28days (MPa)			*At 56days* (MPa)		
	RT	400°C	800°C	RT	400°C	800°C
M1	4.4	4.3	1.2	-	-	-
M2	4.2	3.8	0.8	-	-	-
M3	3.1	2.8	0.5	-	-	-
M2S1	3.3	3.3	1.0	3.9	3.4	1.3
M2S2	4.2	3.6	0.6	4.3	4.0	1.5
M2S3	3.7	3.5	0.4	3.95	4.1	0.8
M1S3P	5.2	4.7	3.1	5.7	6.9	2.4
M2S1P	3.5	4.3	0.2	3.8	5.0	0.32
M3S2P	2.6	2.4	0.4	3.0	3.0	0.92

Fig. 6 presents the behavior of compressive strength, Fc, after curing at 28 and 56 days for mixes M2, M2S1, M2S2, and M2S3 at room temperature. These mixes contain silica fume with three levels of 5%, 10%, and 15% from the weight of cement. It is observed that compressive strength decreases with added silica fume for M2S1 (28 days) by about 7.1% at the test after curing of 28 days compared to M2. In comparison, the compressive strength for specimen M2S1 (56 days) has a noticeable increase of about 3.1% and 10.6% compared to mixes M2 and M2S1 (28 days), respectively.

Moreover, the results of the compressive strengths for M2, M2S2 (28 days), and M2S2 (56 days) in case adding 10% of silica fume ratio at room temperature are presented in Fig. 6. We can notice that mixing M2S2 (56 days) gives the highest value of compressive strength about by 20% and 11.5% as compared to M2 and M2S2 (28 days), respectively. The mix prepared with silica fume =15% showed a slight increase compressive strength for specimen M2S3 (56 days) by about 2.6% and 1.5% as compared to M2 and M2S3 (28 days), respectively.

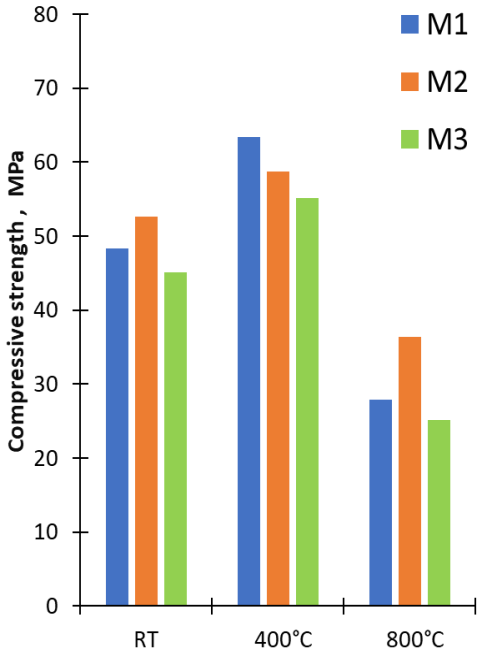


Fig. 5 Compressive strength values at elevated temperatures

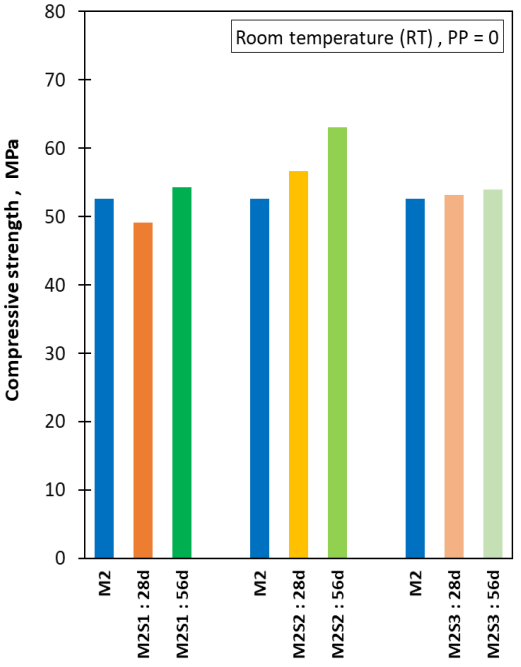


Fig. 6 Effect of silica fume percent on compressive strength at room temperatures.

Fig. 7 presents the behavior of compressive strength after curing for 28 and 56 days for mixes M2, M2S1, M2S2, and M2S3 after exposure to temperatures of 400°C. These mixes contain silica fume with three proportions of 5.0%, 10%, and 15% weight of cement. The results of the compressive strengths for M2, M2S1 (28 days), and M2S1 (56 days) added a 5% silica fume ratio at 400°C. It is observed that compressive strength decreases with added silica fume for M2S1 by about 3.9% at the test after curing of 28 days compared to M2. In comparison, the compressive strength for specimen M2S1 (56 days) slightly increased by about 0.5% and 4.4% compared to mixes M2 and M2S1 (28 days), respectively. Moreover, the results of the compressive strengths for M2, M2S2 (28 days), and M2S2 (56 days) in case adding 10% of silica fume ratio at 400°C are presented in Fig. 7. We can notice that mixing M2S2 (56 days) gives the highest value of compressive strength about by 18.2% and 2.5% as compared to M2 and M2S2 (28 days), respectively. On the other hand, the mix with silica fume =15% showed that compressive strength has a remarkable decrease by about 6.9% after curing of 28 days compared to M2, and compressive strength has a slight increase for specimen M2S3 (56 days) about 3.4% and 10.5% as compared to M2 and M2S3 (28 days), respectively. This result was reported by [7, 17, and 18].

Fig. 8 shows the behaviour of compressive strength after curing 28 and 56 days for mixes M2, M2S1, M2S2, and M2S3 after exposure to temperatures of 800°C. These mixes contain silica fume with three proportions of 5%, 10%, and 15% weight of cement. The results of the compressive strengths for M2, M2S1 (28 days), and M2S1 (56 days) added a 5% silica fume ratio at 800°C. It is observed that compressive strength decreases with added silica fume for M2S1 by about 0.8% at the test after curing of 28 days compared to M2. In comparison, the compressive strength for specimen M2S1 (56 days) slightly increased by about 6.6% and 7.5% compared to mixes M2 and M2S1 (28 days), respectively. Moreover, the results of the compressive strengths for M2, M2S2 (28 days), and M2S2 (56 days) in case adding 10% of silica fume ratio at 800°C are presented in Fig. 8. We can notice that mixing M2S2 (56 days) gives the highest value of compressive strength about by 31.3% and 14.3% as compared to M2 and M2S2 (28 days), respectively. On the other hand, the mixes prepared with silica fume=15% showed that compressive strength has a remarkable decrease with added silica fume for M2S3 at the test after curing of 28 days

compared to M2 and M2S3 (56 days) by about 44.5% and 20.6%, respectively. This result was reported by [7, 17 and18].

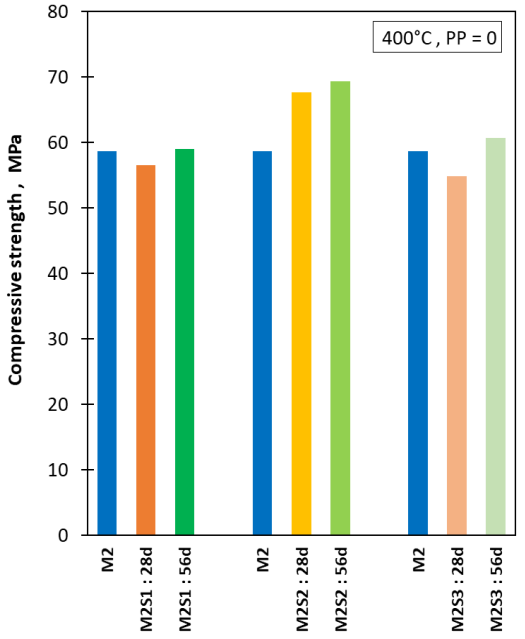


Fig. 7 Effect of silica fume precent on compressive strength at 400°C.

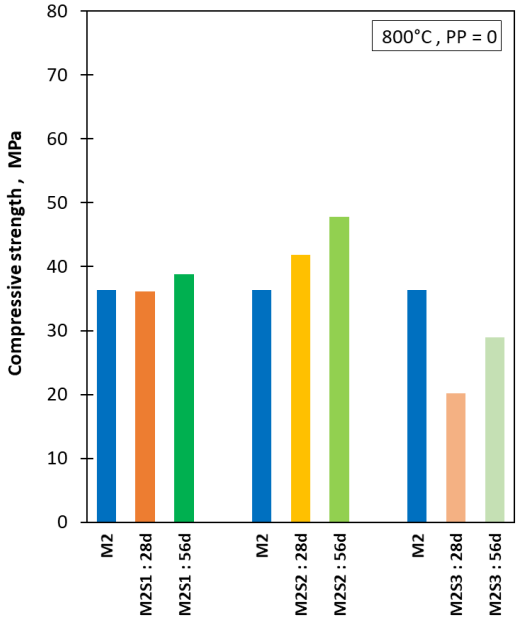


Fig. 8 Effect of silica fume precent on compressive strength at 800°C.

The polypropylene fibers were added to concrete mixes to study behavior compressive strength of 28 days by about 0.106%, 0.211%, and 0.317% from the concrete volume at RT, 400°C, and 800°C, was implemented by Ahmad et al [17]. The results concluded that the highest effect of the presence of polypropylene fibers =0.211 with 5.0% of silica fume and W/(C+SF) = 0.31 at 400°C.

Fig. 9 shows the behavior of compressive strength after curing for 28 and 56 days for mixes at room temperature. The results of the compressive strengths for M2, M2S1P (28 days), and M2S1P (56 days) added a 5% silica fume ratio at room temperature. It is observed that compressive strength increases with added polypropylene fibers for M2S1P (56 days) by about 42.2% and 6.0% compared to mixes of M2 and M2S1P (28 days), respectively. In comparison, the compressive strength in the case of adding 10% of silica fume ratio for specimen M3S2P (56days) has a noticeable increase of about 54.3% and 14.6% compared to mixes M3 and M3S2P (28days), respectively. The mixes prepared with silica fume =15% showed a decrease in compressive strength for M1S3P by about 24.5% after 28 days compared to M1. Also, we can notice that mixes prepared with silica fume =15% showed that compressive strength decreases for M1S3P by about 24.5% at the test after curing for 28 days compared to M1. M1S3P (56 days) gives a slight improvement of about 6.9% compared to specimen M1S3P (28 days).

Fig. 10 presents the behavior of compressive strength after curing for 28 and 56 days for mixes after exposure to temperatures of 400°C. The results of the compressive strengths for M2, M2S1P (28 days), and M2S1P (56 days) with adding of 5% silica fume ratio at 400°C. It is observed that compressive strength showed a remarkable increase with added polypropylene fibers for M2S1P(56 days) by about 27.7% compared to mixes of M2 and a slight increase by about 1.0% compared to mix M2S1P(28 days). In comparison, the compressive strength in the case of adding 10% of silica fume ratio with polypropylene fibers for specimen M3S2P (56days) has a noticeable increase of about 32.1% and 4.9% compared to mixes M3 and M3S2P (28days), respectively. On the other hand, the specimens prepared with silica fume =15% with polypropylene fibers =0.211% showed that compressive strength has a minor improvement for M1S3P at the test after curing for 28 days compared to M1. Also, we can notice that mix M1S3P (56 days) gives a noticeable improvement of about 7.8% compared to specimen M1S3P (28 days). This result was reported by [10 and 19].

Fig. 11 shows the behaviour of compressive strength after curing for 28 and 56 days for mixes after exposure to temperatures of 800°C. The results of the compressive strengths are for M2, M2S1P (28 days), and M2S1P (56 days) with adding a 5% silica fume ratio with added polypropylene fibres at 800°C. It is observed that compressive strength has a negligible decrease for M2S1P (28 days) compared to mixes of M2 and a remarkable improvement for specimen M2S1P (56 days) by about 25.0% compared to mix M2S1P (28 days). In comparison, the compressive strength in the case of adding 10% of silica fume ratio with polypropylene fibers for specimen M3S2P (56days) has a noticeable increase for specimen M3S2P (56days) of about 57.5% and 2.8% compared to mixes M3 and M3S2P (28days), respectively. On the other hand, the mixes prepared with silica fume =15% with polypropylene fibres =0.211% showed that compressive strength gives a noticeable increase for specimen M1S3P (56 days) of about 20.4% and 8.0% compared to mixes M1 and M1S3P (28days), respectively. This result was reported by [10 and 19].

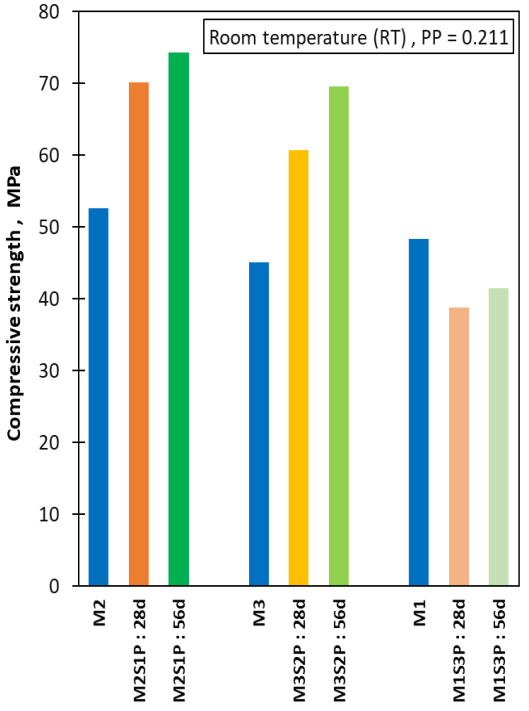


Fig. 9 Effect of polypropylene fibers on compressive strength at room temperatures.

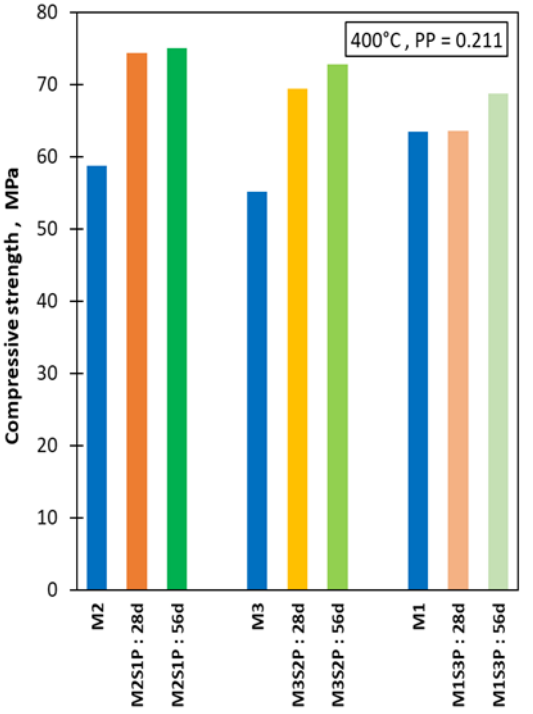


Fig. 10 Effect of polypropylene fibers on compressive strength at 400°C.

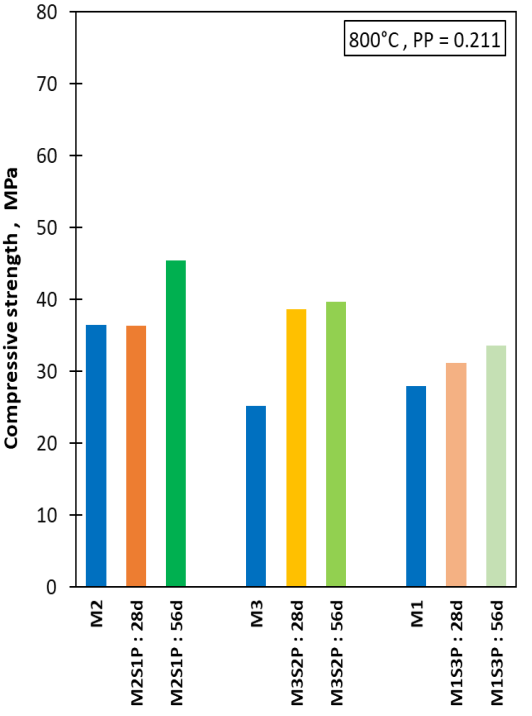


Fig. 11 Effect of polypropylene fibers on compressive strength at 800°C.

3.2. The behavior of splitting tensile strength at different temperature

Fig. 12 presents the behaviour of mixes M1, M2, and M3 for tensile strength after 28 days, at different temperatures. These mixes were exposed to a temperature of 400 °C. From the data shown in the figure, we can notice that at room temperature, the mixture of M1 with W/C = 0.25 records the highest value of tensile strength as compared to M2 and M3. We notice that the mix M1 with W/C = 0.25 gives a higher value of tensile strength by about 13.1% and 53.5% compared to M2 and M3. While the mixes were exposed to a high temperature of 800 °C, the results indicated that the mixture of M1 with W/ C = 0.25 gives the highest value of tensile strength reach to 33.3% and 58.3 % as compared to M2 and M3.

Fig. 13 presents the behavior of splitting tensile strength after curing for 28 and 56 days for mixes M2, M2S1, M2S2, and M2S3 at room temperature. These mixes contain silica fume with three proportions of 5%, 10%, and 15% weight of cement. The results of the tensile strengths for M2, M2S1 (28 days), and M2S1 (56 days) added 5% of the silica fume ratio at room temperature. It is observed that tensile strength decreases with added silica fume for M2S1 by about 27.2% at the test after curing of 28 days compared to M2. While the tensile strength for specimen M2S1 (56 days) has a noticeable increase of about 18.1% and M2S1 (28 days). Moreover, the results of the tensile strength for M2, M2S2 (28 days) and M2S2 (56 days) in case adding 10% of silica fume ratio at room temperature are presented in Fig. 13. We can notice that specimen M2S2 (56 days) has a slight improvement of tensile strength as compared to M2 and M2S2 (28 days), respectively. On the other hand, the mixes prepared with silica fume =15% showed that It is observed that tensile strength decreases with added silica fume for M2S3 by about 13.5% at the test after curing for 28 days compared to M2 at room temperature. In comparison, the tensile strength for specimen M2S3 (56 days) has a noticeable increase of about 6.7% and M2S3 (28 days).

Fig .14 presents the behavior of splitting tensile strength after curing for 28 and 56 days for mixes M2, M2S1, M2S2, and M2S3 after exposure to temperatures of 400°C. These mixes contain silica fume with three proportions of 5%, 10%, and 15% weight of cement. The results of the tensile strengths for M2, M2S1 (28 days), and M2S1 (56 days) added a 5% SF ratio at 400°C. It is observed that tensile strength decreases with added silica fume for M2S1 by about 15.1% at the test after curing for 28 days compared to M2. In comparison, the tensile strength for specimen M2S1 (56 days) slightly increased by about 3.0% for M2S1 (28 days). Moreover, the results of the splitting tensile strengths for M2, M2S2 (28 days), and M2S2 (56 days) in the case of adding 10% of silica fume ratio at 400°C are presented in Fig. 14. We can notice that mixed M2S2 (56 days) gives the highest value of tensile strength about by 5.2% and 11.1% as compared to M2 and M2S2 (28 days), respectively. On the other hand, the mixes prepared with silica fume=15% showed that tensile strength has a remarkable decrease with added silica fume for M2S3 by about 8.6% at the test after curing for 28 days compared to M2 at 400°C. And tensile strength has a considerable increase for specimen M2S3 (56 days), about 17.1% compared to M2S3 (28 days). This result was reported by [7, 17, and 18].

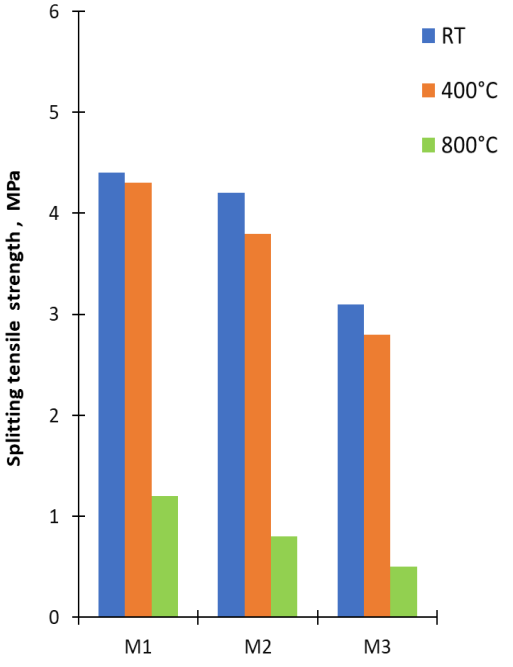


Fig. 12 splitting tensile strength values at different temperatures

Fig. 15 presents the behavior of indirect tensile strength after curing for 28 and 56 days for mixes M2, M2S1, M2S2, and M2S3 after exposure to temperatures of 800°C. These mixes contain silica fume with three proportions of 5%, 10%, and 15% weight of cement. The results of the tensile strengths

for M2, M2S1 (28 days) and M2S1 (56 days) added 5% of silica fume ratio at 800°C. It is observed that tensile strength has a remarkable increase with added silica fume for M2S1 by about 62.5% and 30.0 % at the test after curing for 56 days compared to M2, and M2S1 (28 days), respectively. While the results of the tensile strengths for M2, M2S2 (28 days), and M2S2(56 days) in the case of adding 10% of silica fume ratio at 800°C are presented in Fig. 15. We can notice that tensile strength has a remarkable decrease with added silica fume for M2S2 by about 25.0% at the test after curing of 28 days compared to M2. Moreover, M2S2 (56 days) has a noticeable improvement of about 87.5% compared to M2. On the other hand, the specimens prepared with silica fume =15% showed that tensile strength has a remarkable decrease with added silica fume for M2S3 by about 50% at the test after curing of 28 days compared to M2. Additionally, mix M2S3 (56 days) has a remarkable improvement of about 50% compared to M2S3 (28 days). This result was reported by [7, 17, and 18].

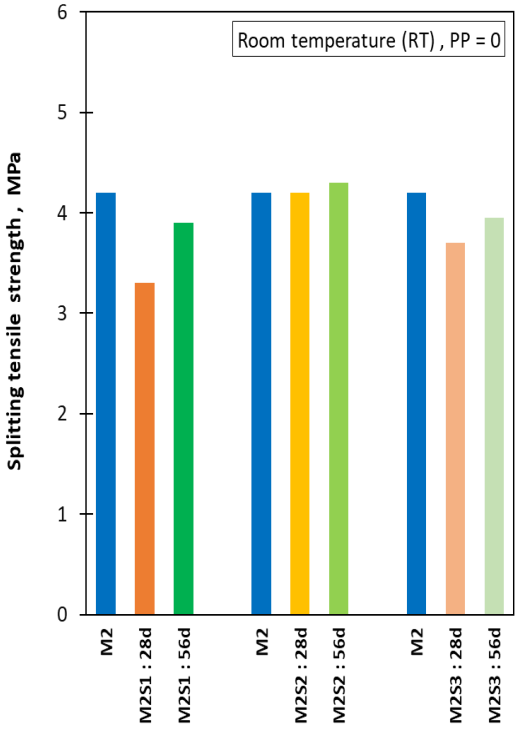


Fig. 13 Effect of silica fume percent on splitting tensile strength at room temperatures.

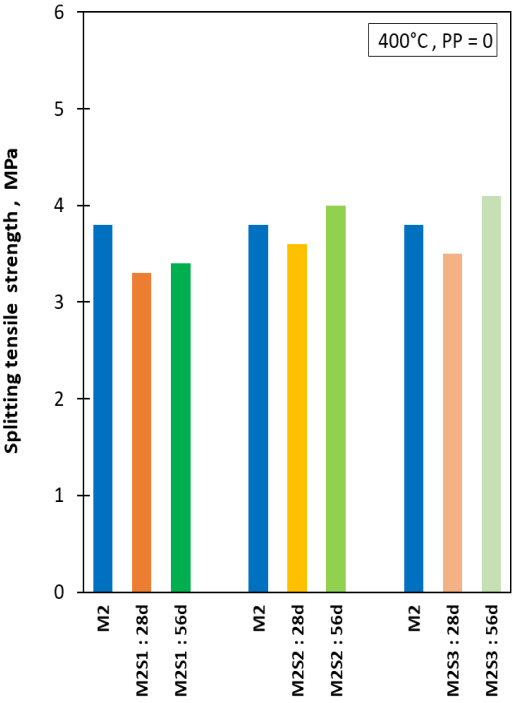


Fig. 14 Effect of silica fume percent on splitting tensile strength at 400°C.

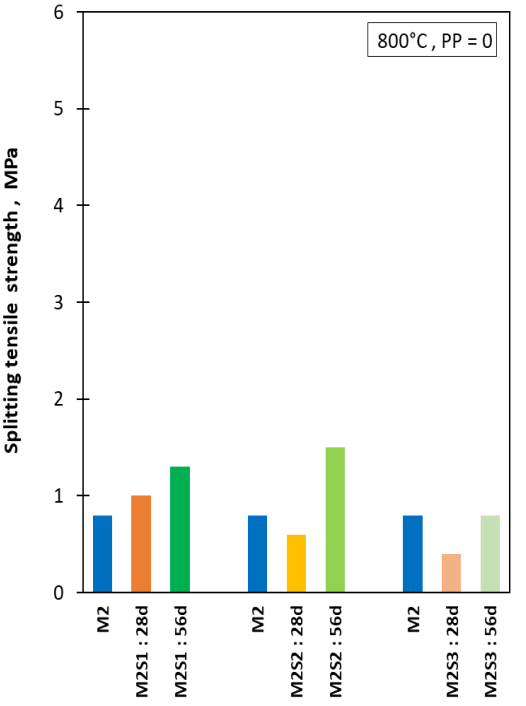


Fig. 15 Effect of silica fume percent on splitting tensile strength at 800°C.

3.3. Water Permeability Test

To evaluation the durability of the concrete was studied by examining the water penetration depth of specimens M2S1P, M3S2P and M1S3P at room temperature after curing for 90 day, as given in Fig. 16. These mixes contain silica fume with three proportions of 5.0%, 10%, and 15% weight of cement with polypropylene fibers =0.211%.

From the figure, we can notice that specimen M3S2P, W/(C+SF) = 0.37, silica fume =10%, and polypropylene fibers =0.211 gives lower porous due to the silica fume activity which consumes Ca (OH)2 and produces excessive C-S-H gel. The formation and nature of the C–S–H were mainly controlled by the active elements Si and Ca, which resulted from the hydration process, which caused a reduction in lower penetration depth to 10mm. While specimens M2S1P and M1S3P recorded penetration depth values of about 12.6 mm and 20.7mm at room temperature. The specimens and the penetration depth of water at room temperature are given in Fig. 17.

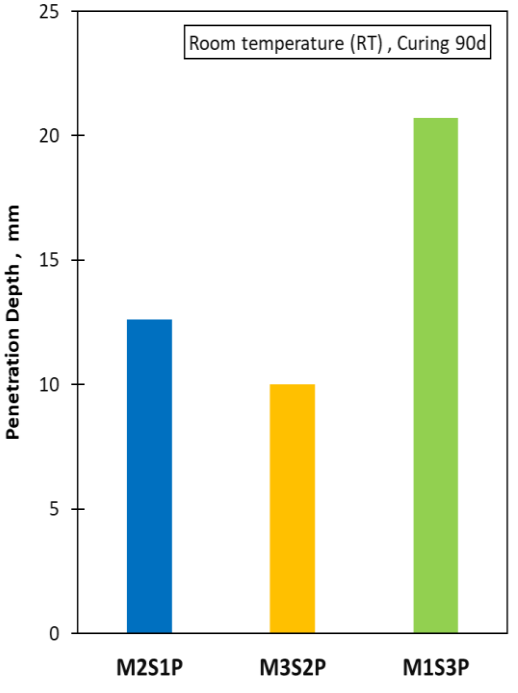


Fig.16 Water penetration depth of mixes at room temperature.

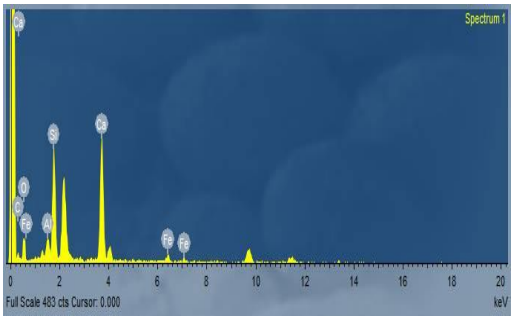
Fig.17 Split M3S2P specimen at room temperature.

3.4. Scanning Electron Microscope (SEM) Result

After the specimens were tested at different temperatures, the surfaces of the specimen were examined using SEM and EDS. The primary elements in the chemical mixtures were C, O, Mg, Si, and Ca. The C-S-H and Ca (OH) 2 gels create the structure for every ingredient. This work shows the effects of temperatures at RT, 400 °C, and 800 °C on the surface of tested specimens made from M2S2 and M2S1P mixes.

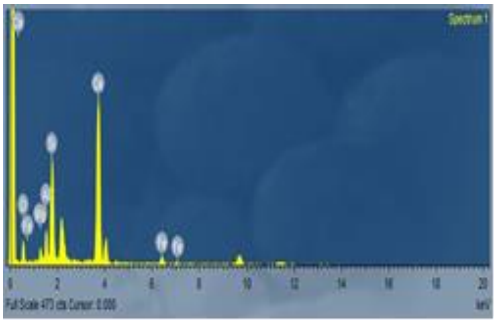
SEM micro graphically inspection and EDS spot analysis of specimen M2S2 taken at various temperatures are shown in Figs. 18 and 19. While Fig. 18 displays the weight (%) of each constituent for the specimen M2S2. When the temperature reached 400 °C, the amount of the elements O and Ca grew; however, when it reached 800 °C, it began to decline. The Si element grew at 400 °C while decreasing at 800 °C, which led to a decline in the strength of concrete till failure. M2S2 analysis using EDS was performed on the Ca/Si atomic ratio to examine the chemistry of C-S-H produced in the hydrated cement paste matrix. The chemical roles of the Ca and Si created during the hydration process clearly impacted the C-S-H formation's chemistry. As can be seen in Fig. 19, the intensified compacted microstructure of the cement matrix was brought on by the low Ca/Si ratio (b). As a result, the M2S2 mix's Ca/Si ratio marginally dropped at T > 400 °C, increasing the compressive strength compared to that at room temperature.

Element	Wt. %	At. %	Ca/Si %
O K	47.62	62.82	0.115
Al K	2.11	1.65	
Si K	41.56	31.23	
Ca K	6.81	3.59	
Fe K	1.90	0.72	



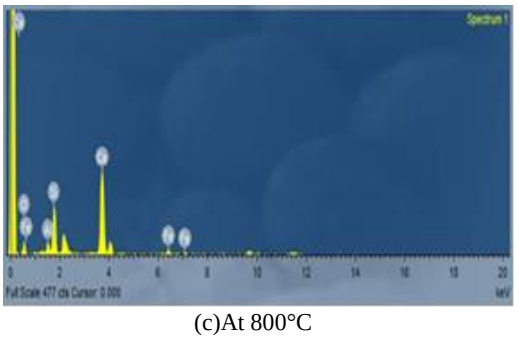
(a) At room temperatures

Element	Wt. %	At. %	Ca/Si %
O K	45.05	63.07	1.16
Mg K	2.93	2.70	
Al K	5.29	4.39	
Si K	16.86	13.45	
Ca K	27.91	15.60	
Fe K	1.96	0.79	



(b) At 400°C

Element	Wt. %	At. %	Ca/Si %
O K	46.29	65.14	1.19
Al K	3.86	3.22	
Si K	17.32	13.88	
Ca K	29.29	16.45	
Fe K	3.24	1.30	

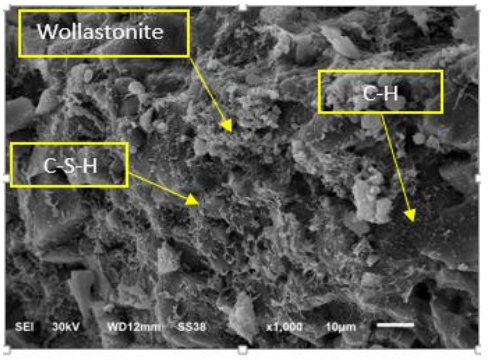


(c)At 800°C

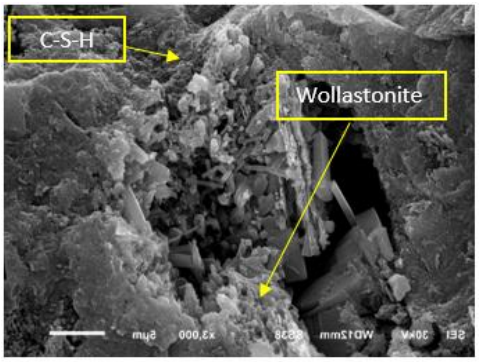
Fig.18. EDS results for M2S2 at different temperatures.

Figs. 20 and 21 show, for specimen M2S1P, analyses of EDS tests and SEM images taken at RT, 400, and 800 C, respectively. The percentage of the elements Ca and Si increases as the temperature rises to 400 °C before declining at 800 °C, which increases the concrete's strength to failure, as demonstrated by the specimen M2S1P. In addition, as shown in Fig. 25, the M2S1P mix's microstructure deteriorated the most when exposed to the high temperature of 800 °C (c). The SEM image shows that CSH and CH peaks were produced, which are important hydration products. This image also appeared to have additional wollastonite (CaOSiO2) photos. Due to the pozzolanic interaction between the CH created by cement hydration and SF, which causes a noticeable consumption of the CH with increasing curing time until 28 days hydration, the CH images decrease as the initial curing time increases.

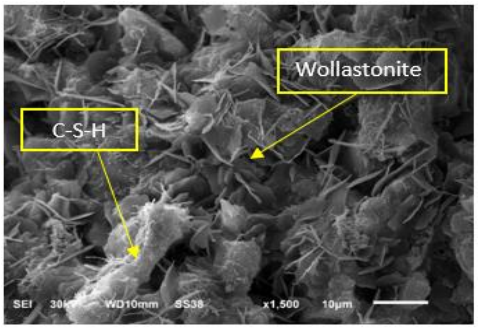
The fact that the peaks are identified for some resulting hydration products (CSHs, CASHs, and CH), as well as traces of unreacted silicates like C3S and -C2S after 28 days of curing, may be responsible for the slight decrease in the SEM of CSH images (CSH is amorphous and ill-crystalline) with increasing concrete ages. Additionally, different peaks for free quartz and CaCO3 are found. On the other hand, the internal autoclaving reaction in OPC that results in free Al2O3 in FA causes the SEM pictures to produce more CASHs. All binding yields are thermally destroyed when OPC-FA or silica fume composite is fired at 400°C, which causes a dramatic depression in the pictures of CASHs, CSHs, and CH in SEM. The SEM images for CH, CSHs, and CASHs entirely disappeared after firing at 800 °C. At the same time, C3S and b-C2S were expanded once more, demonstrating the destruction of the binding phases at 800 °C that transformed into unreacted silicates. The CaO phase is discovered due to the decarbonization process at 750°C. The chemical interactions of free oxides (CaO, SiO2, MgO) at this temperature also show evidence of akermanite (Ca2MgSi2O7) and larnite (Ca2SiO4) phases.



(a) At 25°C



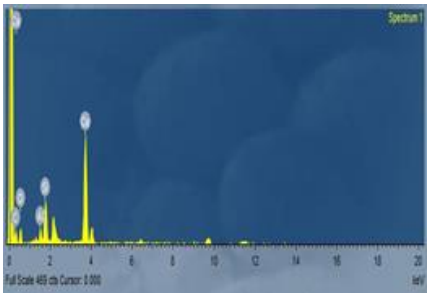
(b) At 400°C



(c) At 800°C

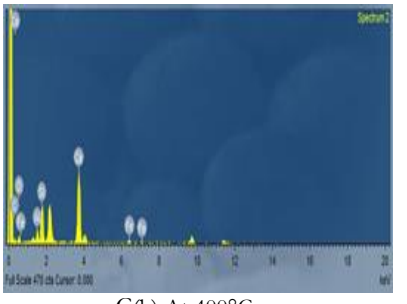
Fig.19 SEM micrographs for specimen M2S2 at different temperatures.

Element	Wt. %	At. %	Ca/Si %
C K	34.36	47.16	1.82
O K	39.13	40.32	
Al K	2.09	1.28	
Si K	6.79	3.99	
Ca K	17.63	7.25	



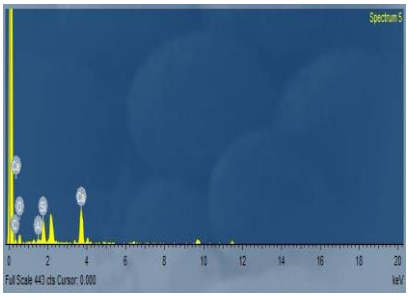
(a) At 25°C

Element	Wt. %	At. %	Ca/Si %
C K	39.43	54.67	
O K	29.21	30.41	
Al K	2.80	1.73	1.405
Si K	8.84	5.24	
Ca K	17.72	7.36	
Fe K	1.99	0.59	



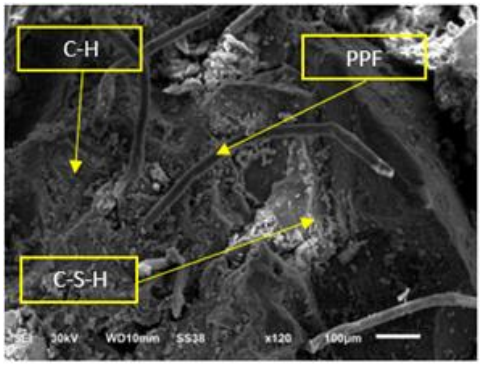
C(b) At 400°C

Element	Wt. %	At. %	Ca/Si %
C K	25.69	37.82	1.7
O K	41.22	45.56	
Al K	1.30	0.85	
Si K	9.28	5.84	
Ca K	22.51	9.93	

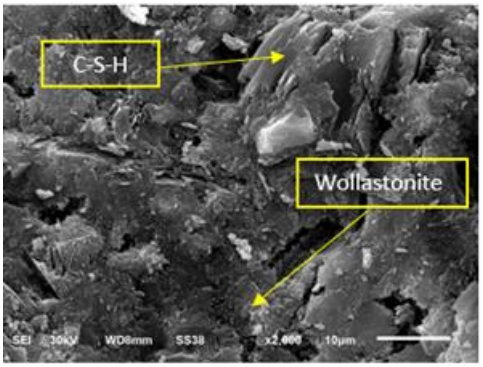


(c) At 800 °C

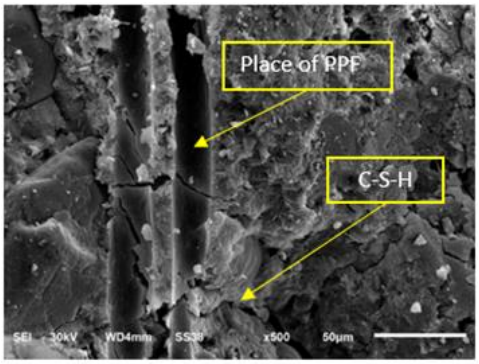
Fig.20 EDS analysis for specimen M2S1P at different temperatures.



(a) At 25°C



(b) At 400°C



(c) At 800°C

Fig.21 SEM micrographs for specimen M2S1P at different temperatures.

4. Conclusion

This experimental work allows us to conclude the following:

- The highest compressive strength value of specimen M1 (w/c = 0.25) was at exposing to a temperature of 400 °C. While, exposing to a temperature of 800 °C causes highest value of the compressive strength for mix M2 (w/ c = 0.31).
- At room temperature, the highest compressive strength improvement achieves by about 20% for mix M2S2 (56 d) in the case of silica fume =10%. In contrast, with added polypropylene fibers =0.211, compressive strength has a significant increased for sample M2S1P (56 d) by about 41.2%, in the case of silica fume =5%.
- At 400°C, the highest compressive strength improvement achieves by about 18.2% for mix M2S2 (56 d) in the case of silica fume =10%. In contrast, with added of polypropylene fibers =0.211, compressive strength has a significant increased for sample M2S1P (56 d) by about 27.9%, in the case of silica fume =5%.
- At 800°C, the highest compressive strength improvement achieves by about 31.3% for mix M2S2(56 d) in the case of silica fume =10%. In contrast, with added of polypropylene fibers =0.211, compressive strength has a significant increase for sample M2S1P (56 d) by about 24.7%, in the case of silica fume =5%.
- At room temperature, the highest tensile strength improvement achieves by about 2.4% for mix M2S2 (56 d) in the case of silica fume =10% compared to M2. While, the highest tensile strength recorded improvement by 29.5% for mix M1S3P (56 d) in the case of silica fume =15%, with polypropylene fibers =0.211.
- At 400°C, the highest tensile strength improvement achieves by about 5.2% for mix M2S2(56 d) in the case of silica fume =10% compared to M2. While, the highest tensile strength recorded improvement by 46.8% for mix M1S3P (56 d) in the case of silica fume =15%, with polypropylene fibers =0.211.
- At 800°C, the highest tensile strength improvement achieves by about 87.5% for mix M2S2 (56 d) in the case of silica fume =10% compared to M2. While, the highest tensile strength recorded for mix M1S3P (28 d) in the case of silica fume =15%, with polypropylene fibers =0.211.
- The lowest porous penetration depth of water for mixture containing W/(C+SF) = 0.37, of silica fume =10%, and polypropylene fibers =0.211%.

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