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Influence of admixing natural pozzolan as partial replacement of cement and microsilica in UHPC mixtures

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HIGHLIGHTS

- Use of natural pozzolan as partial replacement of cement and microsilica in UHPC mixtures.
- No negative impact on the key properties of UHPC due to addition of natural pozzolan.
- Significant saving of microsilica and cement due to use of natural pozzolan.

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ABSTRACT

Ultra-high performance concrete (UHPC), comprising of high amounts of cement and microsilica as binder and micro filler, is a new generation of concrete possessing highly dense microstructure with excellent mechanical properties, durability characteristics and ductility (fracture toughness). However, the use of high amounts of cement and microsilica makes UHPC costly and environment-unfriendly. In the present study, an effort is made to study the effects on properties of UHPC mixtures due to incorporation of natural pozzolan (NP) as a partial replacement of cement and microsilica. Targeting a significant reduction in consumption of cement and microsilica without compromising the required workability, six UHPC mixtures were considered. The first mixture was taken as control mixture without replacement of cement and microsilica by NP. In the second and third mixtures, 25 and 50% microsilica was replaced by NP, respectively. In fourth, fifth and sixth mixtures, 10, 20 and 30% of cement was replaced by NP, respectively. Specimens were moist-cured for 14 days before exposing them to air in the laboratory conditions. All the six UHPC mixtures were tested to determine the mechanical properties (compressive and tensile strengths, modulus of elasticity, and fracture toughness), drying shrinkage, and chloride permeability. Test results indicate that the replacement of cement (up to 30%) and microsilica (up to 50%) by NP did not significantly affect the fresh and hardened properties of UHPC mixtures confirming the potential of using NP for producing cost-effective and environment-friendly UHPC mixtures.

1. Introduction

Ultra-high performance concrete (UHPC) is relatively a new concrete material developed in 1990s in France [1]. UHPC possesses much better mechanical and durability properties as compared to high-performance concrete due to its dense microstructure and low permeability. This tremendous improvement in the properties of UHPC is mainly due to limiting water to cementitious materials ratio below 0.2, using high amounts of cement and microsilica, eliminating coarse aggregate to achieve homogeneity in particle sizes, implementing high pressure and high temperature curing regimes, and using fibers to enhance the tensile strength, toughness and ductility [2]. However, the use of high amounts of cement and microsilica in UHPC has some disadvantages, such as higher cost of cement and microsilica (if not locally available) and generation of more carbon dioxide. The higher cost of binders and environmental concerns put constraints for the applications of UHPC. This makes it interesting to select a suitable material, more preferably cheaper and locally available in abundance, which can partially replace the cement and microsilica without compromising on the required properties of UHPC.

Attempts have been made to utilize various minerals, such as natural pozzolan, limestone powder, fly ash, pulverized steel slag, and cement kiln dust, as partial replacements of cement, microsilica

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and even sand in UHPC [3]. The presence of a mineral admixture in the concrete mixture can adapt to the kinetics of hydration reaction, decrease heat evolution and produce additional C-S-H hydrates making the matrix denser [4].

The natural pozzolan is a volcanic powder containing siliceous or siliceous and aluminous materials without considerable lime, and is being used since long as one of the mineral admixtures in concrete [5]. The silica from natural pozzolan reacts with the calcium hydroxide formed through primary hydration of cement, producing the secondary C-S-H hydrates that is advantageous in minimizing the negative effect caused by hot weathering conditions and improving the strength and durability by densification of the concrete matrix [5]. Natural pozzolan also fills the capillary pores, which is advantageous in enhancing strength and durability and reducing drying shrinkage of concrete [6].

Several studies considered partial replacement of cement by natural pozzolan to achieve an improvement in the strength and durability [7–9]. Shannag [10] found that the natural pozzolan could be added in quantity up to 25% by weight of the cement without decreasing the strength of specimens at the age of 28 days and up to 35% to match the strength of Portland cement at the age of 90 days. Al-Chaar et al. [9] reported that the cement along with natural pozzolan has lower heat of hydration, which enhance concrete workability and durability including resistance against sulfate attack and alkali silica reactions. However, because of a little higher angularity of the particles of the natural pozzolan it slightly reduces the workability of concrete [10] that can be compensated by the use of superplasticizer, particularly at a low water to cementitious materials ratio.

The present study was aimed at exploring the possibility of producing UHPC mixtures utilizing the natural basaltic pozzolan available in abundance in Saudi Arabia, without any significant negative effects of incorporation of natural pozzolan on the fresh and hardened properties of UHPC. For this purpose, firstly, several trial mixtures of UHPC were considered by varying the dosage of Saudi natural pozzolan for partial replacement of cement and microsilica. The trial mixtures were tested for workability in terms of flow spread diameter. The maximum replacement levels were decided based on meeting the minimum requirement of workability. Five UHPC mixtures containing different dosages of natural pozzolan as partial replacements of cement and microsilica were selected for evaluation of their performances in terms of their mechanical properties, shrinkage and durability characteristics. For comparison, a reference mixture without natural pozzolan was also prepared and tested.

2. Experimental program

2.1. Materials

2.1.1. Cement and microsilica

Type I cement, conforming to ASTM C150 [11], with a specific gravity of 3.15 was used in this study. Microsilica available in the local market (Elkem® microsilica), with a specific gravity of 2.25 was used. The oxide compositions of cement and microsilica (MS) used in the present study are presented in Table 1.

Table 1
Oxide compositions of cement and microsilica.

Oxide	Percentage (by weight)	
	Cement	Microsilica
CaO	64.35	0.48
SiO_2	22.00	92.5
Al_2O_3	5.64	0.72
Fe_2O_3	3.80	0.96
K_2O	0.36	0.84
MgO	2.11	1.78
Na_2O	0.19	0.5

2.1.2. Natural pozzolan

Natural pozzolan used for producing concrete materials in Saudi Arabia, is obtained by crushing volcanic ash sourced from basalt plateaus, Herrat, in the Western region of Saudi Arabia. The physical and chemical properties of the Saudi natural pozzolan are comprehensively reported by various researchers [12–15]. Physical and chemical characteristics of the Saudi natural pozzolan, as reported by these researchers have some small differences due to different locations of sourcing of the volcanic ash and crushing to different levels of fineness. For example, the natural pozzolan with more fineness possesses more specific gravity than the same natural but ground to a lower fineness [12]. The differences in sampling and testing methods may also be considered reasons behind small discrepancies in the physical and chemical properties of the Saudi natural pozzolan reported in literature. As a supplementary cementitious material, the Saudi natural pozzolan is reported to satisfy the requirements of ASTM C618 [16] for Class N natural pozzolan [13]. Moufti et al. [17] found the Saudi natural pozzolan satisfying pozzolanic reactivity as per the Italian Standards.

The chemical composition and particle size distribution of the natural pozzolan (NP) used in this study are shown in Table 2 and Fig. 1, respectively. The specific surface area (fineness) of the natural pozzolan was 6666 cm^2/g against the specific surface area of 3700 cm^2/g for Type I Portland cement. Due to high fineness, the natural pozzolan used in the present work had a relatively high specific gravity of 3.0.

2.1.3. Aggregate

Local fine dune sand with water absorption of 0.4% (by weight) and specific gravity of 2.65 was used as the aggregate-phase of the UHPC mixtures. Grading of the fine dune sand is shown in Table 3.

2.1.4. Superplasticizer

The superplasticizer used in the mixtures was MasterGlenium51®. It was supplied by a local manufacturer in Saudi Arabia. Properties of the superplasticizer are presented in Table 4.

2.1.5. Steel fibers

The properties of steel fibers used in the present study are shown in Table 5.

2.2. UHPC mixtures

An UHPC mixture consisting of a cement content of 900 kg/m^3 and MS content of 220 kg/m^3, developed earlier by the authors [18], was considered as a reference mixture without any replacement of cement or MS by NP. In order to select maximum levels of partial replacements of cement and MS by NP, five UHPC mixtures were considered on trial basis. In first two mixtures, MS was partially replaced by 25 and 50% NP, respectively. In three other mixtures, cement was partially replaced by 10, 20 and 30% NP, respectively. The maximum levels of replacement of microsilica and cement were considered as 50% and 30%, respectively, ensuring that the minimum required flow (determined in accordance with ASTM C1437 [19] is achieved in the range of 200 ± 20 mm. The details of partial replacements of cement and MS by NP in the selected five UHPC mixtures are presented in Table 6. Weight of constituents materials for producing one cubic meter of selected UHPC mixtures, calculated using absolute volume method of design of concrete mixtures, are shown in Table 7. Although the quantities of cementitious materials, superplasticizer, and steel fibers are constant for all UHPC mixtures, as shown in Table 6, the quantities of sand are different for each mixture to balance the differences in total absolute volumes due to different specific gravities of the cementitious materials (cement, microsilica and natural pozzolan).

2.3. Mixing, flow test, casting and curing

The ingredients of the UHPC mixtures were mixed in a high shear capacity mixer. Charging and mixing of the ingredients were done in accordance with the procedure as reported in literature [20].

Table 2
Oxide compositions of the natural pozzolan used.

Oxide	Percentage (by weight)
CaO	8.06
SiO_2	42.13
Al_2O_3	15.33
Fe_2O_3	12.21
K_2O	0.84
MgO	8.50
Na_2O	2.99
P_2O_5	1.37
TiO_2	0.60
Loss on ignition	1.60

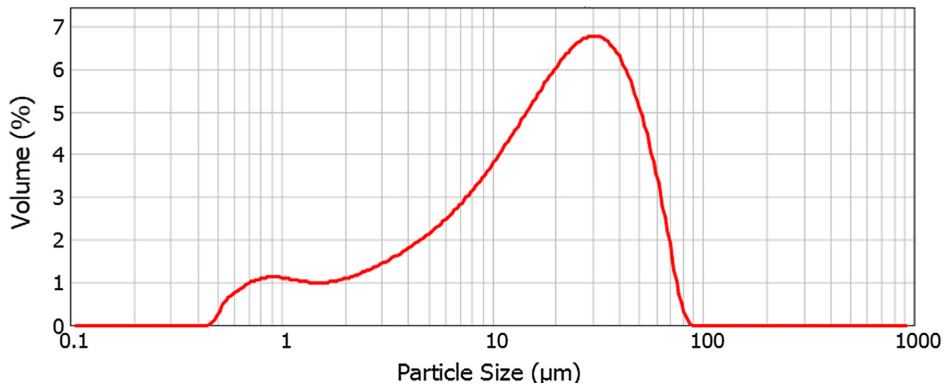

Fig. 1. Particle size distribution of the natural pozzolan (NP) used in the study.

Table 3
Grading of fine dune sand.

Sieve #	Size	% Passing
4	4.75 mm	100
8	2.36 mm	100
16	1.18 mm	100
30	600 μm	76
50	300 μm	10
100	150 μm	4

Table 4
Properties of the superplasticizer.

Property	Description
Appearance	Brown liquid
Specific gravity @ 20 °C	1.08 ± 0.02 g/cm^3
pH-value @ 20 °C	7.0 ± 1.0
Alkali content	≤5.0
Chloride content	≤0.1%

Table 5
Properties of the steel fibers.

Property	Description
Type	Smooth plain copper coated steel fibers
Diameter	0.22 mm
Length	13 mm
Aspect ratio	59
Tensile strength	2500 MPa

As soon as mixing was completed, each UHPC mixture was tested for consistency. ASTM C1437 [19] standard test method for measuring flow of hydraulic cement was used to comply with the recommendations outlined in Ductal® reference T006, Operating Procedure-Flow Test, [21]. In flow test, mini slump cone was filled with UHPC mixture, and then removed slowly to allow the mixture to flow on the table, then the flow table raised and dropped 20 times and the average flow spread diameter of the mixture was recorded as flow value. Flow domain classifications of freshly mixed UHPC, as recommended in Ductal® reference T002, Operating Procedure-Cylinder and Prism Preparation [22], were adopted to grade the consistency of the mixtures based on their average flows measured after 20 blows. According to Ductal® reference T002, Cylinder and Prism Preparation [22], the flows of the UHPC mixtures are classified into three Domains. Domain A-"stiff" mixtures with average flow of <200 mm; Domain B-"fluid" with average flow ranging from 200 mm to 250 mm; and Domain C-"highly fluid" with average flow >250 mm. For each of the six UHPC mixtures, four replicate samples of fresh concrete were tested and average of the flow values of the replicate samples were reported as representative value for each mixture.

After completion of mixing process, the mixtures were cast into molds within 20 min by pouring the material into the molds placed on a vibrating table. The molds filled with the UHPC mixture were vibrated for about 10–20 s after filling the whole mold to consolidate the mixture. The specimens in molds were covered with plastic sheets to prevent moisture loss. After casting, the specimens were kept in the molds for a duration of six hours before demolding them and starting the curing, so that they can gain some strength before curing.

Each mixture was cured using water-soaked burlap curing method that consisted of covering the specimens with jute sheets and then sprinkling water over it once in a day. All specimens were moist-cured for the first 14 days and then exposed to the air in the laboratory conditions for a duration of 90 days.

2.4. Details of the tests on hardened UHPC specimens

Table 8 shows the details of UHPC specimens used for conducting various tests for each of the six mixtures, along with the respective test standards [23–28]. As can be seen from Table 8, the specimens were tested for compressive strength after 7 days and 14 days of moist curing and then tested at the age of 28 and 90 days after exposing them to the air. Other tests except shrinkage, were conducted after moist curing the specimens for 14 days and then exposing to the air for another 14 days (i.e., after a total duration of 28 days). Casting of specimens, storage of specimens before demolding, curing and testing were conducted in the laboratory conditions where a normal room temperature of 25 ± 3 °C and a low relative humidity of 60 ± 5% were maintained. Shrinkage was monitored up to a duration of 4 months after moist curing for 14 days.

For determining compressive strength at 7, 14, 28, and 90 days, twelve cubical specimens were tested for each of the six UHPC mixtures. For each of the testing ages, three replicate specimens were used and the average of the values of the compressive strength for three replicates was reported as representative value. Similar to the compressive strength tests, three replicate specimens were used for each of the six mixtures for conducting other tests on hardened UHPC specimens, as listed in Table 8. The average of the values for replicate specimens was taken as representative value.

Table 6
Details of partial replacements of cement and MS by NP in the selected UHPC mixtures.

Mixture ID	Replacement	Cement (%)	MS (%)	NP (%)
M0 (Reference)	No replacement	100	100	0
M1	Replacement of MS by NP	100	75	25
M2		100	50	50
M3	Replacement of cement by NP	90	100	10
M4		80	100	20
M5		70	100	30

Table 7
Weight of constituents materials for producing one cubic meter of selected UHPC mixtures (water/binder = 0.145 for all mixtures).

Ingredients	M0	M1	M2	M3	M4	M5
Cement (kg)	900	900	900	810	720	630
MS (kg)	220	165	110	220	220	220
NP (kg)	0	55	110	90	180	270
Water (kg)	163	163	163	163	163	163
Superplasticizer (kg)	40	40	40	40	40	40
Steel fibers (kg)	157	157	157	157	157	157
Sand (kg)	1005	1021	1036	1002	998	994

Table 8
Details of test method and specimens for testing after curing.

Test	Test Method	Specimen Dimensions	Test Age
Compressive strength	ASTM C39 [23]	100 × 100 × 100 mm cube	7, 14, 28 and 90 days
Modulus of elasticity	ASTM C469 [24]	75 × 150 mm cylinder	28 days
Split tensile strength	ASTM C496 [25]	75 × 150 mm cylinder	28 days
Fracture Toughness	ASTM E1290 [26]	40 × 40 × 160 mm prism specimens (notched at mid span)	28 days
Shrinkage	ASTM C157 [27]	50 × 50 × 250 mm prism	Up to 4 months
Chloride permeability	ASTM C1202 [28]	75 × 150 mm cylinder	28 days

3. Results and discussion

3.1. Workability

The standard deviations of the flow values measured using four replicate samples for each of the six UHPC mixtures varied in the range of 0.81–1.41 mm. Lower values of the standard deviation for the measured values of the flow indicate reliability of the test results. The average values of the flow of the six mixtures were used to plot Figs. 2 and 3. It can be observed from Figs. 2 and 3 that all the UHPC mixtures satisfied the workability requirements as their flow values were in the range of targeted flow (200 ± 20 mm, i.e., 180–220 mm). This targeted range of flow was considered to meet the requirements of flow ranging from "slightly stiff" to "fluid" domains, according to Ductal® reference T002, Cylinder and Prism Preparation [22]. The maximum limit for replacements of microsilica and Portland cement by natural pozzolan were kept as 50% and 30%, respectively. This was decided considering the fact that the addition of natural pozzolan beyond these limits would decrease the flow below minimum value of 180 mm, as can be seen from Figs. 2 and 3, unless the dosage of superplasticizer is increased which may cost more than saving due to an increase in the dosage of natural pozzolan.

Reduction in the workability of concrete mixtures due to addition of highly reactive pozzolanic mineral admixtures has been reported due to increase in the cohesiveness of concrete depending on particle shape and size, specific surface area, and reactivity of the pozzolanic mineral admixtures [29]. Further, as mentioned earlier, a little higher angularity of the particles of the natural pozzolan also contribute to the reduction in the workability of concrete [10]. In the present work, a significant reduction in flow with increase in the quantity of NP was noticed. The reduction in flow was noticed in both cases, when NP was used as a partial replacement of microsilica as well as when used as a partial replacement of Portland cement. In case of partial replacement of microsilica by the NP, the decrease in the flow at a higher natural pozzolan content may be attributed to the fact that the NP, with a considerable amount of lime (8.06% by weight), had high reactivity as compared to that of the microsilica with a negligible amount of lime (0.48% by weight). In case of the NP partially replacing the Portland cement, the flow decreased at a higher dosage of the NP because the NP used had high reactivity due to its higher specific surface area (6666 cm^2/g) as compared to that of the of Portland cement (3700 cm^2/g).

The linear best fitting of the data plotted in Figs. 2 and 3 suggests that replacing 60% and 35% of MS and cement, respectively, by NP would produce UHPC mixtures with flow diameter of about 179 mm that meets the target minimum workability of 180 mm without additional water and SP. Therefore, the maximum replacement levels of MS and cement by NP may be considered up to 60% and 35%, respectively. However, in the present study, the maximum replacement levels of MS and cement by NP were considered as 50% and 30%, respectively, to have workability more than the target minimum workability of 180 mm.

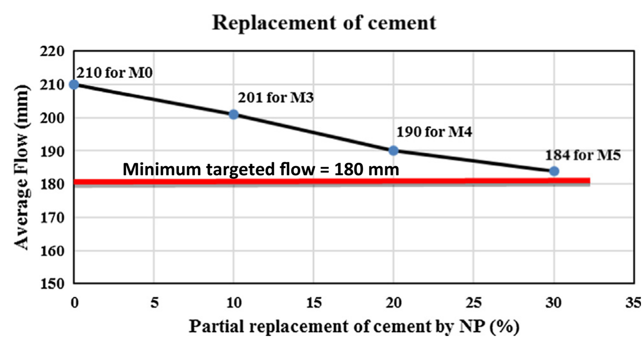

Fig. 3. Variation of flow with increasing level of replacement of cement by NP.

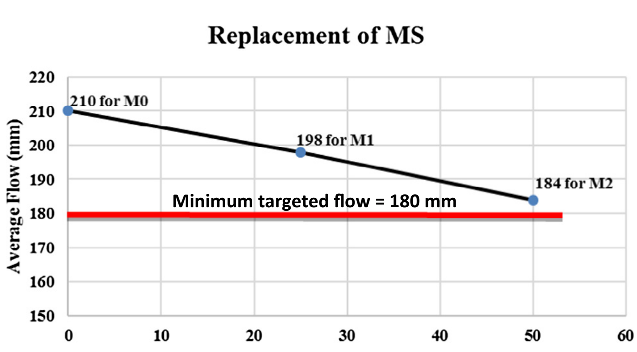

Fig. 2. Variation of flow with increasing level of replacement of MS by NP.

3.2. Compressive strength

Table 9 shows the compressive strengths of all the six UHPC mixtures tested at the age of 7, 14, 28 and 90 days. The standard deviation of compressive strength values determined by testing 72 specimens varied in the range of 0.14 to 2.40 MPa. The standard deviations for 80% specimens were found to be less than 1 MPa. All the specimens were moist-cured for 14 days then exposed to air up to the age of 90 days. As mentioned earlier, the values of compressive strength, presented in Table 9, are averages of the compressive strengths of three replicate specimens. The compressive strength data for all the UHPC mixtures were plotted as shown in Fig. 4. As compared to the reference mixture (M0), the maximum reduction in strength of UHPC mixtures due to the partial replacement of microsilica or cement by natural pozzolan is noted to be only around 11% at the age of 7 days. The difference in the strength of UHPC containing pozzolan and reference UHPC mixture narrowed down with the age and the maximum difference remained only about 6% at the age of 90 days. This observation concurs with previous research findings that the pozzolanic activity of NP in the formation of cementitious hydrates increases with time reducing porosity and increasing cohesiveness of the hydrated cementitious matrix leading towards significant gain of the strength up to 90 days [7,10,13,14,30]. Khan and Alhozaimy [13] and Celik et al. [14] presented the results of their detailed experimental studies on normal concrete mixtures incorporating the Saudi natural pozzolan including the effects of addition of the Saudi natural pozzolan on formation of hydration products and reduction in porosity of hydrated cementitious matrix with age. They [13,14] reported the trends of evolution of strength of normal concrete mixtures with age similar to what observed in the present study on the performance of UHPC mixtures containing the Saudi natural pozzolan. This observation confirms that the natural pozzolan can be incorporated into UHPC mixtures to reduce the consumption of microsilica and Portland cement without significant loss of long-term compressive strength. It can be further noted that all the mixtures including the reference one have achieved compressive strength above 150 MPa at the age of 90 days without water curing after 14 days.

Table 9
Summary of compressive strength results for all BC specimens.

Mixture ID	Compressive Strength (MPa) Testing age (days)			
	7	14	28	90
M0	124.1	132.9	143.0	161.6
M1	115.5	123.0	138.8	154.8
M2	113.5	122.0	138.2	152.4
M3	116.0	125.3	140.4	157.2
M4	116.5	125.1	132.2	153.7
M5	110.0	124.5	130.6	151.0

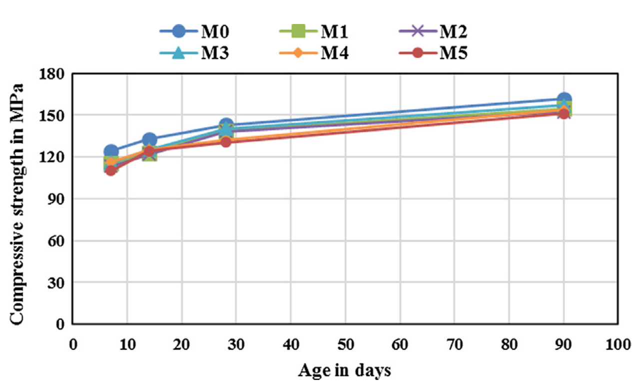

Fig. 4. Variation of compressive strength with age.

3.3. Modulus of elasticity, splitting tensile strength and fracture toughness

Table 10 shows the test results pertaining to modulus of elasticity, splitting tensile strength, and fracture toughness of all six UHPC mixtures, tested at the age of 28 days (exposed to air for 14 days after 14 days of the moist-curing).

The modulus of elasticity of the mixtures were calculated using the stress-strain plots as shown in Figs. 5 and 6. It can be observed from Figs. 5 and 6 that for all the UHPC mixtures, the initial portion of the stress-strain curves are almost linear, therefore, the modulus of elasticity was taken as the slope of the straight-line portion of the stress-strain diagram. It can be seen from Fig. 7 that except the mixture M5 with 30% cement replaced by natural pozzolan, all four mixtures (M2 through M4) had almost similar modulus of elasticity, very close to the value for the reference mixture (M0). However, even the mixture M5 had a modulus of elasticity value acceptable for UHPC and comparable to the value for M0 with only 16% reduction. Since the modulus of elasticity depends on the combination of aggregate and cement matrix properties, just like compressive strength, the observed reduction in modulus of elasticity with higher replacement of NP is expected considering the observed lower compressive strength at higher NP contents. It can further be noted from Figs. 5 and 6 that, in case of both partial replacement of microsilica and cement by natural pozzolan, the

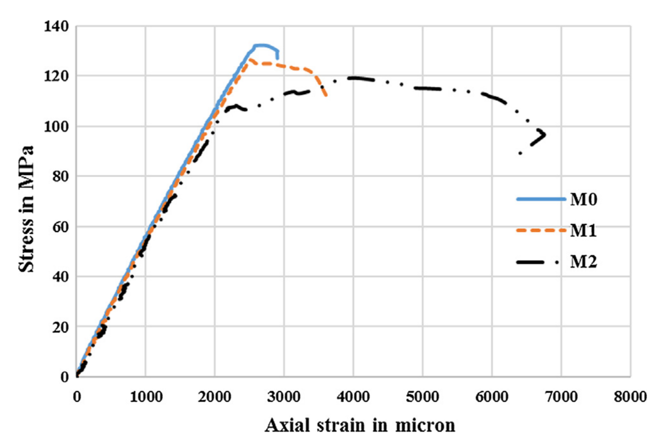

Fig. 5. Stress-strain curves of the UHPC mixtures with replacement of MS by NP.

Table 10
Modulus of elasticity, splitting tensile strength and fracture toughness of UHPC mixtures tested at the age of 28 days.

Mixture ID	M0	M1	M2	M3	M4	M5
Modulus of Elasticity (GPa)	56	53	53	54	52	47
Splitting tensile strength (MPa)	18.0	17.7	17.7	17.8	17.6	17.4
K_{ic} (MPa$\sqrt{m}$)	2.83	2.58	2.64	2.78	2.71	2.16

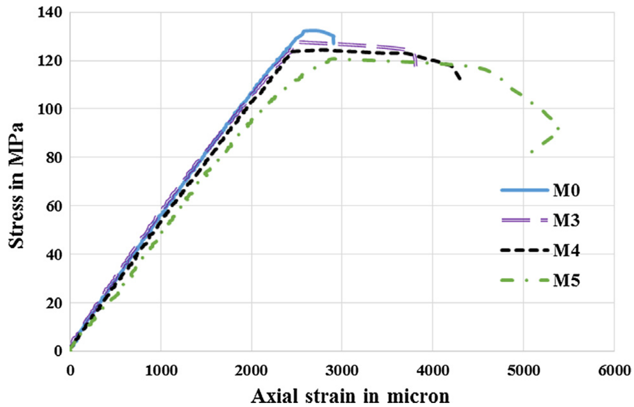

Fig. 6. Stress-strain curves of the UHPC mixtures with replacement of cement by NP.

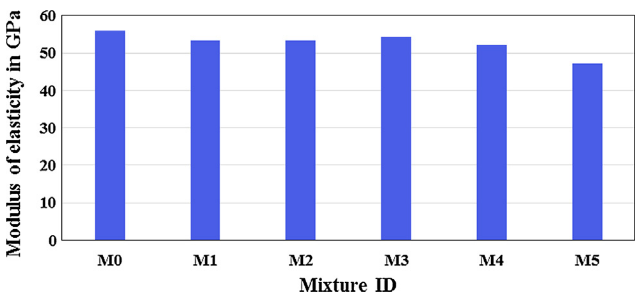

Fig. 7. Modulus of elasticity of UHPC mixtures.

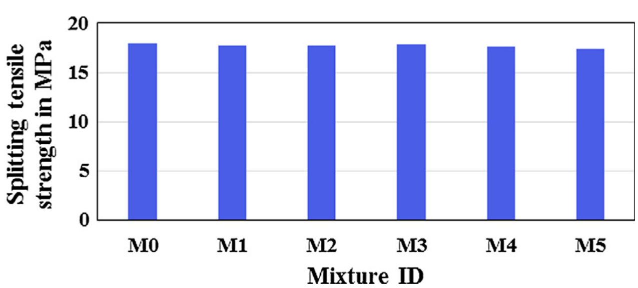

Fig. 8. Splitting tensile strength of UHPC mixtures.

peak load is slightly decreasing with a very significant increase in ductility with increase in the dosage of natural pozzolan. The increased ductility at higher NP content follows from the general characteristics of materials, such as concrete and other ceramics, which become more brittle as compressive strength increases.

The comparison of splitting tensile strengths of all six mixtures, as shown in Fig. 8, indicates that there is no significant effect of partial replacement of microsilica by natural pozzolan as all the mixtures had splitting tensile strength very close to that of the control mixture. This is because the tensile strength of UHPC is mostly affected by the amount of steel fibers, which was kept same for all the mixtures [1,2].

The plot of fracture toughness of all six mixtures, measured in terms of critical stress intensity factor, K_{ic}, as shown in Fig. 9, indicates that as compared to the control mixture there is no significant reduction in K_{ic} in the mixtures with natural pozzolan except the case of mixture M5 in which 30% cement was replaced by natural pozzolan. The effect of incorporation of the natural pozzolan on fracture toughness is almost similar to the effect on the

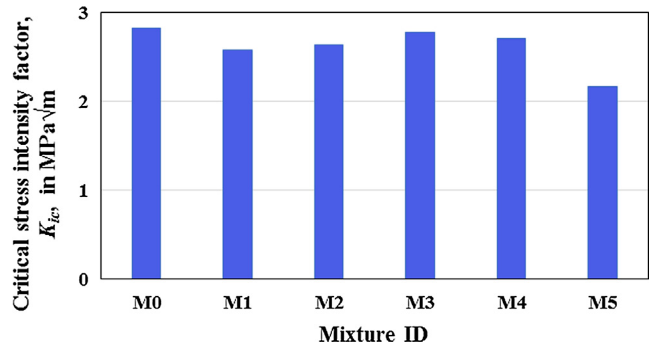

Fig. 9. K_{ic} of UHPC mixtures.

modulus of elasticity. This is because the fracture toughness depends not only on fiber properties but also on matrix mechanical properties, which equally affects modulus of elasticity.

3.4. Drying shrinkage

The drying shrinkage of all six mixtures were measured with time. Monitoring of drying shrinkage reading started directly after curing duration and it lasted up to 120 days of air curing. Plots of drying shrinkage strain recorded at different ages for all the UHPC mixtures are shown in Fig. 10. Shrinkage readings were recorded more frequently at early ages, which refer to the drying shrinkage that took place rapidly in the first days of monitoring. Table 11 shows the 7 days and ultimate drying shrinkage of UHPC mixtures. It can be seen from Fig. 11 that the 7-day drying shrinkage of UHPC mixtures containing natural pozzolan are either similar or less than that of the control mixture, whereas, the ultimate drying shrinkage of these mixtures was significantly lower than the control one. Further, the 7-day drying shrinkage of all the UHPC mixtures were much below the maximum permissible value of 500 μm/m.

Although the Saudi natural pozzolan is rich in MgO (8.5% by weight), the addition of the natural pozzolan decreased the drying shrinkage, as mentioned above, instead of increasing it. The reason behind reduction in the drying shrinkage of the concrete with increase in dosage of Saudi natural pozzolan is reported by Celik et al. [14]. The first cause of reduction of the drying shrinkage with addition of the natural pozzolan is reported to be due to refinement of capillary pores due to pozzolanic reaction obstructing the evaporation of capillary water. Secondly, the unreacted portion of the natural pozzolan acting as aggregate also contributes in reducing the drying shrinkage.

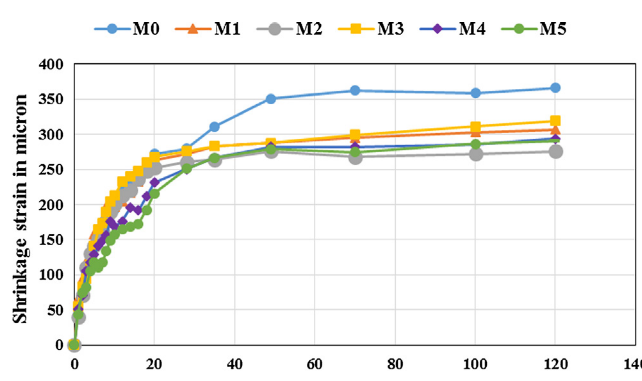

Fig. 10. Variation of drying shrinkage strain of UHPC mixtures with age.

Table 11
7 days and ultimate drying shrinkage of UHPC mixtures.

Mixture ID	M0	M1	M2	M3	M4	M5
7-day shrinkage strains (μm/m)	165	165	140	171	149	118
Ultimate shrinkage strains (μm/m)	366	307	276	319	294	290

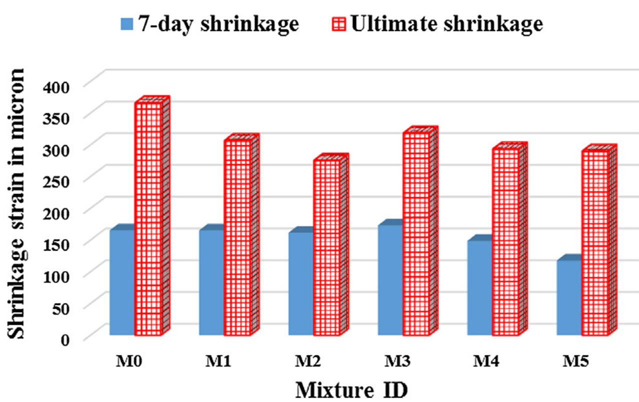

Fig. 11. 7-day and ultimate drying shrinkage of UHPC mixtures.

3.5. Chloride permeability

Rapid chloride penetration test (RCPT) is the most commonly method used to measure chloride permeability in Coulombs (C). Based on the measured values of charges passing through concrete, the chloride permeability can be classified as high (>4000 C), moderate (2000–4000 C), low (1000–2000 C), very low (100–1000 C), and negligible (<100 C) [28].

The results of chloride permeability for all mixtures are presented in Table 12. In addition, the plot of the chloride permeability values with its category classification presented in Fig. 12. It can be seen from Fig. 12 that all the mixtures have 'very low' chloride permeability readings. Moreover, mixtures M0, M1 and M3 has a negligible chloride permeability.

Table 12
Chloride penetration results for all mixtures.

Mixture ID	M0	M1	M2	M3	M4	M5
Chloride permeability (Coulombs)	59	61	119	65	106	136

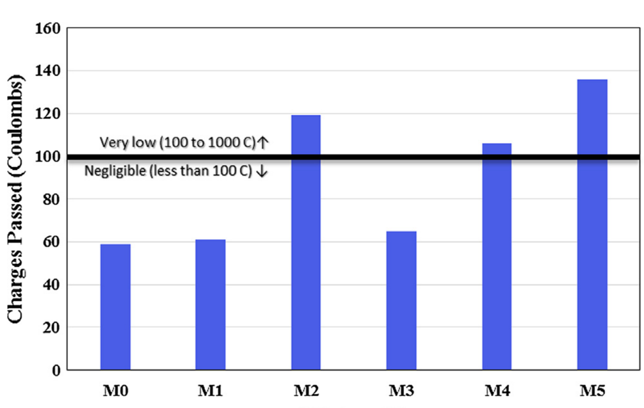

Fig. 12. Chloride permeability of UHPC mixtures.

4. Conclusions

Based on the analysis of experimental data developed in the present study, following conclusions can be drawn:

1. Due to the physical and chemical characteristics of the natural pozzolan used in the present work, the addition of natural pozzolan significantly reduced the workability of UHPC mixtures limiting its maximum dosage to 50% and 30% (by weight) for replacements of microsilica and Portland cement, respectively.
2. Although at early ages, the compressive strength of UHPC mixtures containing natural pozzolan was lower than that of the control UHPC mixture, the difference in the strength of UHPC containing natural pozzolan and control UHPC mixture narrowed down with the age and the maximum difference remained only about 6% at the age of 90 days. It can be further noted that all the UHPC mixtures with natural pozzolan achieved compressive strength above 150 MPa at the age of 90 days without moist curing beyond 14 days.
3. Modulus of elasticity, splitting tensile strength and fracture toughness of all mixtures containing natural pozzolan satisfied the requirements of UHPC. The addition of natural pozzolan enhanced the ductility of the UHPC mixtures.
4. All the UHPC mixtures showed lower values of the drying shrinkage. The 7-day drying shrinkage of all the UHPC mixtures were much below the maximum permissible value of 500 μm/m.
5. All the UHPC mixtures showed 'very low' to 'negligible' chloride permeability indicating a high resistance against reinforcement corrosion.
6. The above observations confirm that the natural pozzolan can be incorporated into UHPC mixtures to reduce the consumption of microsilica and cement without significant loss of mechanical properties and without risk of higher shrinkage and reinforcement corrosion.

Conflict of interest

None.

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