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Microstructure, Compressive Strength and Transport Properties of High Strength Self-Compacting Concretes Containing Natural Pumice and Zeolite

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***Abstract*—**Due to the difficult placement and vibration between reinforcements of reinforced concrete and the defects that it may cause, the use of self-compacting concrete (SCC) is becoming more widespread. Ordinary Portland Cement (OPC) is the most widely used binder in the construction industry. However, the manufacture of this cement results in a significant amount of CO_2 being released, which is detrimental to the environment. Thus, an alternative to reduce the cost of SCC is the use of more economical and environmental mineral additives in partial or total substitution of Portland cement. Our study is in this context and aims to develop SCCs both economic and ecological. Two natural pozzolans such as pumice and zeolite are chosen in this research. This research tries to answer questions including the microstructure of the two types of natural pozzolan and their influence on the mechanical properties as well as on the transport property of SCC. Based on the findings of this study, the studied zeolite is a clinoptilolite that presents higher pozzolan activity compared to pumice. However, the use of zeolite decreases the compressive strength of SCC composites. On the contrary, the compressive strength in SCC containing of pumice increases at both early and long term ages with a remarkable increase at long term. A correlation is obtained between the compressive strength with permeable pore and capillary absorption. Also, the results concerning compressive strength and transport property are well justified by evaporable and non-evaporable water content measurement. This paper shows that the substitution of Portland cement by 15% of pumice or 10% of zeolite in HSSCC is suitable in all aspects.

***Keywords*—**SCC, concrete, pumice, zeolite, durability, transport.

I. Introduction

THE formulations of SCC are characterized by a large volume of paste and mineral addition. According to [1], some health risks and environmental problems could be avoided (white finger syndrome, noise, vibrations ...). The formulations of SCC are characterized by a large volume of paste and mineral addition. If it offers multiple benefits to their users, SCC is also an area of research that has a high growth potential. One disadvantage of SCC is its cost. The alternative to reduce the cost of the SCC is the use of mineral additives which replace a part of cement. Two features are important, the use of chemical additives and Portland cement in large quantity which is necessary in the production of SCC to improve the passing ability, the filling ability and stability. OPC, with a total production of around 3,000 Mt/year, is the dominant binder used in the construction industries [2], [3]. Estimates for global demand for the OPC show that cement consumption will reach nearly 6,000 Mt/year in the next 40 years [3]. Environmental problems caused by 5-7% of CO_2 emissions from the cement industry are constantly increasing. Consequently, the use of pozzolan to replace a portion of the cement in concrete production can be as a convenient choice to reduce pollution and is more economical. This is important for the durability of structures that are in aggressive environments like the Persian Gulf side and industrial area in Iran to consider that they are constantly exposed to aggressive agent. Therefore, economic additions as well as durability issues are considered as vital issues and addressed by researchers around the world including Iran. Consequently, the purpose of this article is to study the influence of two natural pozzolan, widely available in Iran, and particularly pumice from Khash (south east of Iran), and zeolite from Semnan (center of Iran) on different properties of HSSCC.

Currently, very little information is available on the durability properties of HSSCC containing pumice and zeolite. Consequently, the investigation of SCC containing natural pozzolan is beneficial and requires further investigation in fresh and hardened phases and durability properties.

This paper investigates and compares the effect of two different natural pozzolans from Iran (pumice and zeolite) on rheological behavior, compressive strength and transport properties of HSSCC at early ages and up to 365 days. For this purpose, first, the chemical and mineralogical composition as well as the microstructure and the pozzolanic activity of the two natural pozzolan were studied. Then, different tests such as slump flow, V-funnel, L-box, U-tube, J-Ring and sieve, were performed to study the fresh phase of HSSCC, and then mechanical testing was done on hardened states to evaluate the compressive strength of the different prepared mixtures. The tests concerning the transport phenomena were also performed at different ages in order to evaluate the durability properties with time including permeable pores, water absorption, absorption after immersion and boiling, capillary absorption, and water penetration.

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II. Materials

Five concrete mixtures were prepared with the same Portland cement type II content (450 kg/m^3), constant W/Cm ratio of 0.4 and constant gravel to sand ratio of G/S=1. A concrete mixture based on Portland cement was used as the control concrete (HSL). In the other four formulations, HSP10, HSP15, HSZ10 and HSZ15 pumice and zeolite were used respectively as an additive with two different replacement percentages of 10% and 15% by Portland cement. A Portland cement with a specific gravity of 3.15 and a Blaine fineness of 2900 cm^2/g, in compliance with ASTM C150 was used.

The pumice used in this study has a specific surface area of 4220 cm^2/g and a specific gravity of 2.58. The used zeolite as shown in Table I is a siliceous zeolite since it contains a high amount of silica. It has a specific surface area of 4060 cm^2/g and a specific gravity of 2.25. The chemical analysis and particle size distribution (PSD) of cementitious materials are shown in Table I and Fig. 1, respectively.

For all mix designs, crushed angular material of 6-12 mm nominal size was used as a coarse aggregate (gravel), and natural sand with a maximum size of 4 mm was used as a fine aggregate. The physical characteristics of gravel and sand according to ASTM C 27-88 and ASTM C128-97 respectively are shown in Table II. Also, their particle size distributions are shown in Fig. 2. A high range water-reducing admixture (HRWRA), with a specific gravity of 1.11 based on chains of modified poly-carboxylate ether (PCE 180), was used in all mixtures to produce HSSCC. Potable water was also used to prepare concrete mixes. The balance between high flow and high segregation resistance is made possible by the dispersing effect of HRWRA combined with cohesiveness of high concentration of fine particles in additional filler material. The dosage of superplasticizer is experimentally determined from tests on fresh concrete to obtain a slump flow diameter of 700±30 mm for all HSSCCs. Table III shows the mix proportions of the mixtures. To enhance the stability of SCC mixes, 150 kg/m³ limestone powder was used as filler in the five mixtures. By increasing the replacement level of additives from 10% to 15%, the viscosity of fresh concrete and the amount of superplasticizer required to achieve the desired slump flow is also increased. This last is very significant in the HSZ15 mixture and therefore, this mixture is considered to be uneconomical (Table III). From this aspect, although natural zeolite is cheaper than Portland cement, the high demand of superplasticizer in concretes containing high levels of natural zeolite may result in more production costs. Some researchers concluded that, a large amount of superplasticizer is required to produce concrete containing high percentage of zeolite replacement [4]-[6]. Ahmadi and Shekarchi [4] and Tokushige et al. [6] concluded that, the dosage of superplasticizer increased substantially with incorporation of zeolite. The large amount of the required superplasticizer can be justified by the following reasons: i) the fine microstructure of zeolite, ii) increase of volume paste and iii) high surface area of natural pozzolan. Other researches on conventional concrete also confirmed that incorporation of natural zeolite increased the demand of superplasticizer [7], [8].

TABLE I
Chemical Analysis of Portland Cement Type II, Limestone Powder, Pumice and Zeolite

Chemical analysis (% by mass)	Cement (type II)	Lime stone powder	Pumice	Zeolite
Loss on ignition	1.3	42.88	2.26	11.94
SiO_2	21.74	1.19	56.04	69.72
Al_2O_3	5.0	0.85	27.61	13.54
Fe_2O_3	4.0	0.3	0.25	1.26
CaO	63.04	48.82	8.76	0.87
MgO	2	1.58	4.52	2.45
SO_3	2.3	-	-	-
CO_2	-	-	-	-
$CaSO_4$	-	-	-	-
Cl	-	-	-	-
Insoluble residue	0.60	-	-	-
Alkalis (Na_2O%+0.658K_2O %)	1	-	-	-
Na_2O+K_2O	-	4.27	0.41	0.13
Free Cao	1.4	-		
Humidity	-	0.11	0.15	0.09
C_3S	45.5	-	-	-
C_2S	28.0	-	-	-
C_3A	6.5	-	-	-
C_4AF	12.2	-	-	-

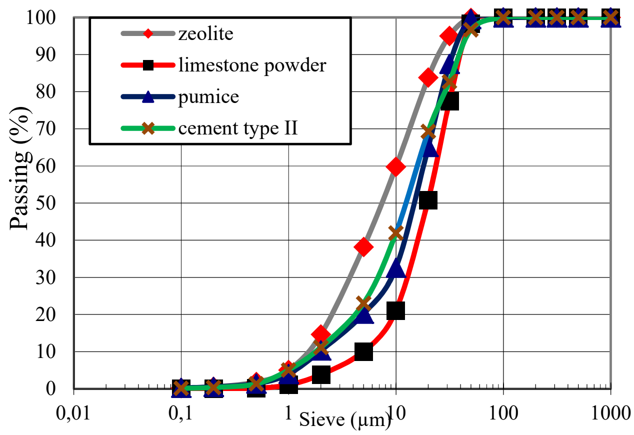


Fig. 1 Particle size distribution of fine materials

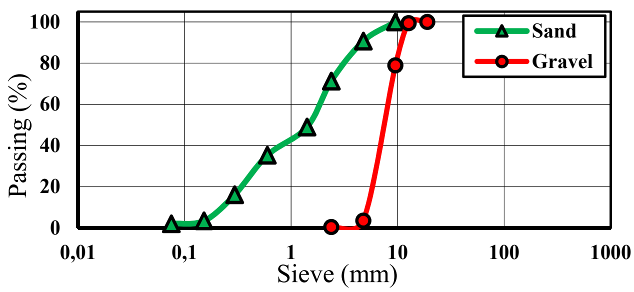


Fig. 2 Particle size distribution of aggregates (gravel and sand)

III. Microstructure Investigation

A. SEM Analysis

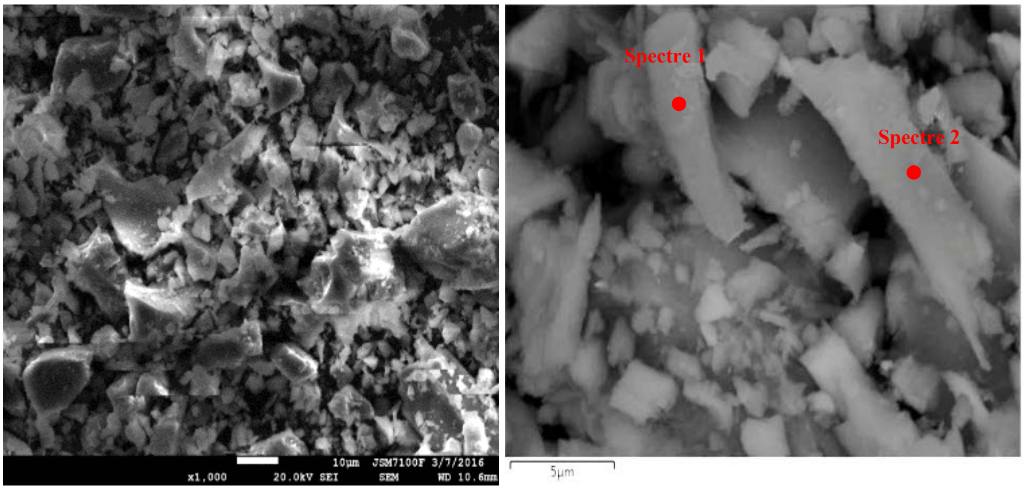
Observations by scanning electron microscopy (SEM) combined with the elemental microanalysis were performed on the studied pozzolans using a JSM 7100F SEM equipped with an Oxford EDS SDD detector. Fig. 3 presents SEM images of pumice powder as well as the corresponding chemical analysis. As indicated, pumice is composed of angular particle that looks like glass material. The main chemical elements present in this pozzolan are Si, Al, K, Na, Ca, Fe, Mg elements. SEM images of zeolite powder with chemical analyses are illustrated by Fig. 4. Zeolite appears to be composed of plate particles (< 2 µm of length) containing the following chemical elements Si, Al, Na, K, Fe, Ca, Mg.

TABLE II
THE PHYSICAL CHARACTERISTIC OF COARSE AND FINE AGGREGATE

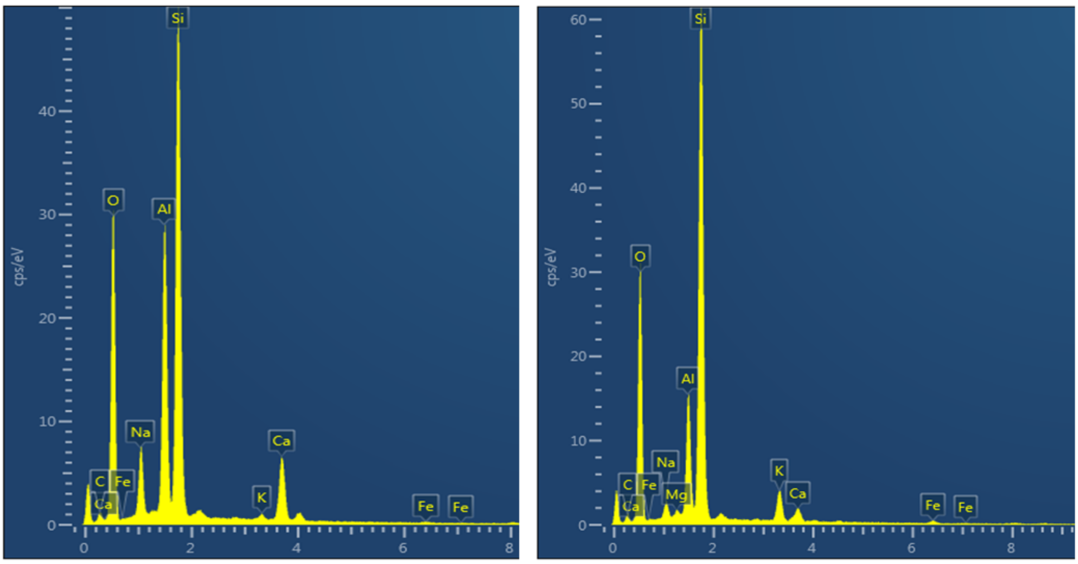
Physical characteristic	Gravel (6-12 mm)	Sand (0-4 mm)
Bulk density	2.72	2.75
Real gravity	2.68	2.58
S. S. D	2.69	2.64
Water absorption (%)	0.625	2.315

TABLE III
MIX DESIGN OF HSSCC MIXTURES (KG/M^3)

Mix name	W	C	w/c	G	S	LP	SP	Z	P
HSL	180	450	0.4	790	790	150	4.85	-	-
HSP10	180	405	0.4	790	790	150	6.2	-	45
HSP15	180	382.5	0.4	790	790	150	6.8	-	67.5
HSZ10	180	405	0.4	790	790	150	8.94	45	-
HSZ15	180	382.5	0.4	790	790	150	21.62	67.5	-

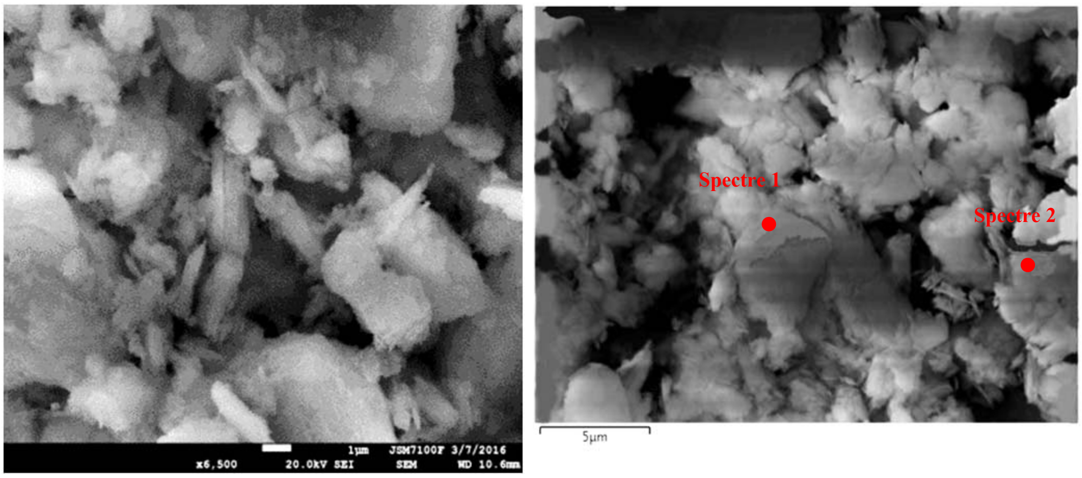


(a)



(b)

Fig. 3 (a) SEM images, (b) Chemical analysis of pumice powder



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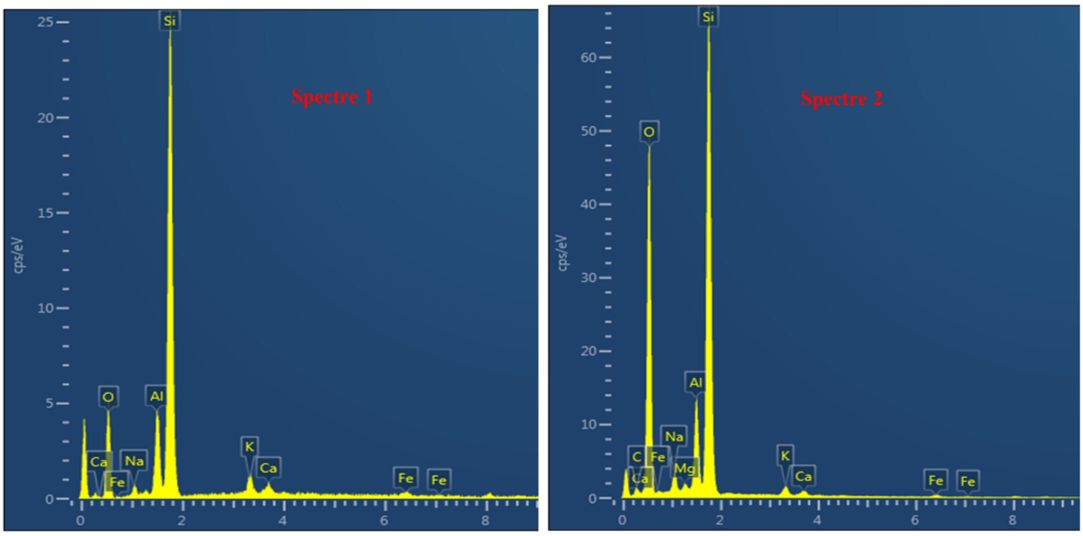

(b)

Fig. 4 (a) SEM images, (b) Chemical analysis of the studied zeolite

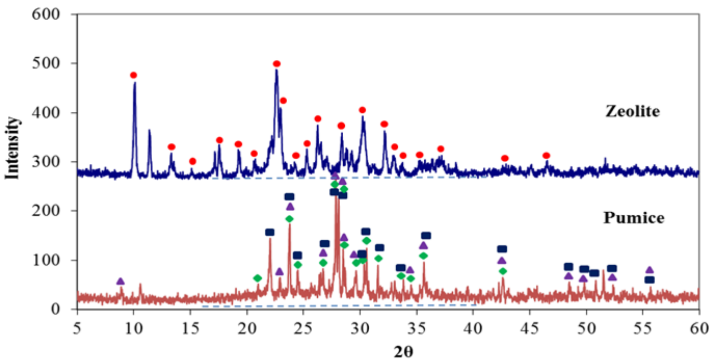

Fig. 5 XRD analysis of zeolite and pumice pozzolan; ●: clinoptilolite, ▲: muscovite, ◆: Anorthite, ■: Anorthite sodian

B. XRD Analysis

Analyses were performed on pozzolan powders using a Bruker D8 X-ray diffractometer with a monochromatic Cu source and a fast linear detector Lynx Eye. XRD results are shown in Fig. 5. XRD diffractogram of the studied zeolite corresponds to clinoptilolite which is one of siliceous natural zeolites. XRD diffractogram of pumice showed that it is composed of admixture of a glassy phase, muscovite, and anorthite minerals.

IV. Experimental Program

A. Mix Design

All concrete mixtures were prepared in a 150 litre mixer. The batching sequence consisted of decant total of the fine and coarse aggregate placed into the mixer, and then mixed for 3 minutes. During this period, 2/3 of the water required was added. Next, cementitious materials were added and mixing was continued for one more minute. After this, the superplasticizer and the remaining water were introduced and the blend was mixed for 2 minutes. The mixer was covered with a plastic cover to minimize the evaporation of the mixing water.

B. Casting and Curing

Cubic and cylindrical samples were cast in accordance with ASTM C31 (2012) and ASTM C511 (2013). After casting, samples were covered with two layers of plastic sheets and placed in temperature controlled room at 22±2 °C for 24 hours. All samples were demolded after 24 hours and cured up to the age of testing in saturated lime solution to prevent possible leaching of $Ca(OH)_2$ from these specimens.

V. Results and Discussion

A. Fresh State

French National Guidelines (AFGC 2000) characterize fresh SCC, taking into account the three main characteristics: i) mobility in unconfined areas, ii) mobility in confined areas and iii) stability: that means the resistance to segregation and bleeding. In order to evaluate the effects of pozzolan on the fresh properties of SCC, slump flow, V-funnel, and L-box tests were performed according to the procedure recommended by EFNARC Committee and also sieve test, J-Ring test and U-tube were performed according to the procedure recommended by AFGC 2000, ASTM C1621 and BS EN206-1, respectively. The slump flow test is one of the most commonly used experiments to measure the properties of SCC. This type of test can give indications as to the rheology of unconfined environment SCC. Depending on the type of application, the mixes with slump flow values ranging from 550 to 850 mm are considered SCC. The segregation tendency of concrete mixes was also evaluated by visual observation during slump flow test as aggregates separate from cement paste close to the edges of speared out concrete. The slump flow of all HSSCC mixes was near to 700±30 mm and no segregation was observed in the mixes (Table IV). The spreading rate of the concrete is also an indication often taken into account (T50 e.g., time to reach a 500-mm spreading diameter, if it takes more than 5 seconds a large plastic viscosity is concluded and if the measured time is less than 1 second, it shows a lower viscosity. In these cases, the risk of segregation and bleeding and creating aureole will increase). The ability of concrete to flow through a restricted area without blockage and segregation was evaluated using V-funnel test. The time of flow from the opening of outlet to the seizure of flow was recorded and results are presented in Table IV. The V-funnel flow time also depends on the type of application, but it is grouped in to two classes [9]. VF1 class: flow time of less than 10 seconds and VF2 class: flow time of between 7 and 27 seconds. Although there are other test methods for assessing passing ability, e.g. L-box, the most common test method is the J-Ring test. The experimental flows of J-ring for concrete mixes based on ASTM C1621 are indicated in Table IV. L-box ratio was carried out on concrete mixes to measure the cohesiveness and ability of SCC to pass through reinforcements without segregation. The L-box ratio is reported to be between 0.7 and 0.9 for normal SCC; however, a range of 0.8 to 1.0 is also proposed by EFNARC guidelines. Results of h2 /h1 ratios relative to this study are presented in Table IV. It can be seen that the values range from 0.77 to 0.93, which are within the specified limits for SCC. It should be noted that three bar L-box height was utilized in this study to simulate more congested reinforcements. The test of the U-box allows the mobility of confined concrete to be characterized and verifies that the installation of the concrete will not be opposite by phenomena unacceptable blockages, the value limit is equal to H2-H1 = 10 mm. This test was performed for all mixes, and the results are presented in Table IV. It can be seen that the range of values is almost within the specified limits. The implementation of SCC, under only the effect of gravity requires a very high fluidity of the material but it is also essential that the concrete maintains a satisfactory stable and perfect homogeneity. Various tests can be used to characterize the resistance to static segregation of SCC to remain homogeneous after its placement until it begins to set. One such test is called "stability sieve", developed by GTM [10] to assess the weight percentage milt (Pmilt noted later). The acceptable limitations are as follow: i) 0% < Pmilt < 15%: Satisfactory stability, ii) 15% < Pmilt < 30%: Critical stability (segregation test necessary on site) and iii) Pmilt > 30%: Very poor stability (systematic segregation, unusable concrete).

TABLE IV
TEST RESULTS OF FRESH HSSCCS

Mix name	Slump flow			L-box		V-funnel t (s)		Sieve test	J-ring		U-tube
	Dia (mm)	T_{50} (s)	h_2/h_1	T_{20} (s)	T_{40} (s)	1min	5min	Segregation (%)	Δ_H (mm)	Dia (mm)	h_2-h_1 (mm)
HSL	731.3	2.03	0.93	1.5	2.2	10	9	4.36	15	702.5	10
HSP10	727.5	2.66	0.84	1.5	3.5	9.25	10.85	4.86	10	715	15
HSP15	732.5	2	0.926	0.98	1.88	8.23	15.75	8.19	25	647.5	5
HSZ10	685	3.45	0.77	2.18	4.1	12	22	8.33	8	630	15
HSZ15	695	2.02	0.86	1.4	2.5	5	7.85	11.62	8	667.5	10

B. Compressive Strength of HSSCC Mixtures

Compressive strength of HSSCC mixes (fc) was measured on a total of 120 cubes of 100×100 mm at 1, 3, 7, 14, 28, 90, 180 and 365 days of aging in accordance with BS 8110: part1: 1997. The strength development of mixes based on average strength of three samples tested at each age is shown in Fig. 6. The slope of the lines (m) of liners relationship between compressive strength and curing age for different mixes is presented in Table V. The gradient of strength-age relationship represents the effect of mix design and materials proportions on rate of strength gain for HSSCC mixtures.

Compressive strength, fc, of all samples for all ages is in the range of 7.04 to 79.7 MPa. The greatest resistance from 3 to 365 days happened for HSP10. The least resistance happened for HSZ15 at all ages. Concrete content of 10% pumice had a very positive effect on the strength from age of 3 days. On the other hand, their amount at 28 days of aging is almost similar to that of control mix. The compressive strength in concrete containing 10% of pumice is 1.06, 1.12, 1.09, 1.02, 1.09, 1.15, and 1.21 times higher than the one of the control concrete at 3, 7, 14, 28, 90, 180, and 365 days of aging, respectively. However, the amount of compressive strength in HSSCC containing 15% of pumice is closer to that in control concrete until age of 90 days. After 90 days of aging, the progress of the compressive strength in HSP15 is more remarkable in comparison with the compressive strength in control mix. Indeed, the increase of the compressive strength for SCC containing 10% and 15% of pumice is most visible at the long-term. The rate of increase of the compressive strength in these mixes (HSP10 and HSP15) is more remarkable at 180 and 365 days. On the contrary, zeolite had a negative impact in the process of increasing the compressive strength. Also, this is more impressive in HSZ15. For example, at 28 days of aging, the compressive strength in control concrete is 1.18 and 1.55 times higher than the one of HSZ10 and HSZ15, respectively. In this way, it can be concluded that the use of zeolite as described here have negative effect on compressive strength in HSSCC compared to that of control concrete (HSL). However, this remark cannot be generalized to all mixture using zeolite. Different results could be found with the use of other type of superplasticizer for example.

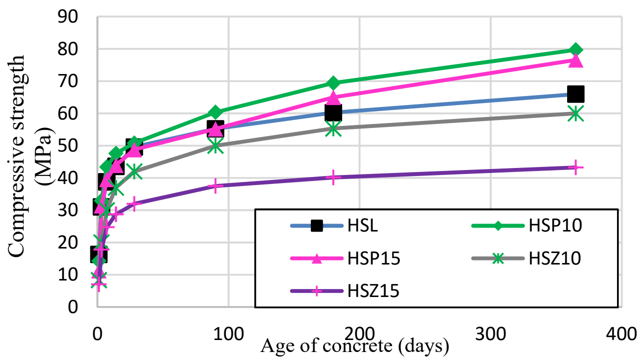

Fig. 6 Evolution of compressive strength, Rc, of HSSCC mixtures with curing time

TABLE V
THE SLOPE OF COMPRESSIVE STRENGTH DEVELOPMENT AT DIFFERENT AGES

Mix name	$m_{1\text{-}3}$	$m_{3\text{-}7}$	$m_{7\text{-}14}$	$m_{14\text{-}28}$	$m_{28\text{-}90}$	$m_{90\text{-}180}$	$m_{180\text{-}365}$
HSL	7.34	1.94	0.69	0.43	0.09	0.06	0.03
HSP10	9.36	2.6	0.6	0.23	0.15	0.1	0.057
HSP15	10.1	2.03	0.63	0.35	0.1	0.11	0.064
HSZ10	5.85	2.49	1	0.36	0.13	0.06	0.03
HSZ15	5.38	1.74	0.57	0.23	0.09	0.03	0.02

C. Hydration Analysis

- Evaporable and non-evaporable water content measurement

The main purpose of thermal analysis that conducted is to measure the content of evaporable and non-evaporable water at 105 °C of binder pastes. These last have the same composition as the binder in the tests concretes but without limestone and using less amount of superplasticizer. The amount of evaporable water can be linked to the porosity. The non-evaporable water is considered as an important and reliable indicator of the hydration progress and in the modification of microstructure. In this way, thermal measurement of evaporable and non-evaporable water content can be useful to justify the mechanical behavior and durability properties of the studied HSSCCs. The evaporable water content corresponds to the mass loss of water between 105 °C and 20 °C (1). Also, the non-evaporable water content corresponds to the mass loss of water between 1000 °C and 105 °C (2). The measurements were carried out on binder pastes. The powders obtained were put in crucibles and placed in a furnace. The samples are carried in the ambient temperature to 1000 °C with a rate of 10 °C per minute and a bearing of 20 hours at 105 °C and 2 hours at 1000 °C. The evaporable water content (We) and non-evaporable water content at 105 °C (Wne) are calculated by:

$$W_e = \frac{W_{20°C} - W_{105°C}}{W_{20°C}} \quad (1)$$

$$W_{ne}\ at\ 105°C = \frac{W_{105°C} - W_{1000°C}}{W_{105°C}} \quad (2)$$

where W_e is evaporable water content; W_{ne} is non-evaporable water content; $W_{20°C}$ is the mass in ambient air; $W_{105°C}$ is the mass of the sample after drying at 105 °C; $W_{1000°C}$ is the mass of the sample after heating at 1000 °C. More evaporable water content indicates a high porosity and likely low mechanical strength. Moreover, the non-evaporable water content in paste can well justify the behavior of the sustainability of studied HSSCCs. More the non-evaporable water content presents pozzolanic-reaction stronger in the relative mix. The result relative to evaporable and non-evaporable water is shown in Fig. 7 and Fig. 8, respectively. According to this result, the amounts of the evaporable and non-evaporable water decrease and increase with curing time respectively. Thereby, the amount of evaporable water in paste containing 10% of pumice is less compared to that in control mixture at all ages. For HSP15 sample, it was found that, this trend started from 7 days of age. According to these results, the quantity of porosity and compressive strength in mixture containing pumice can be well justified at each curing time by consideration the amount of evaporable and non-evaporable water. In the paste containing zeolite, the evaporable water content is higher compared to that in control mix, particularly in the paste with 15% of zeolite. This fact can be linked to the low mechanical behavior obtained with formulations containing zeolite pozzolan. On the other hand, the great non-evaporable water content in mixture containing zeolite can be associated to a high pozzolanic reaction.

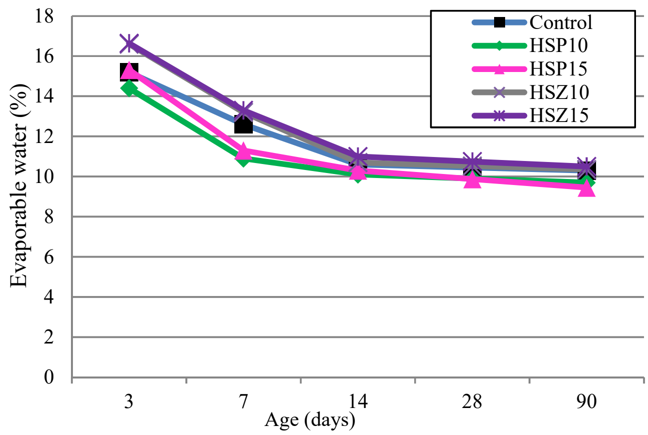

Fig. 7 Evaporable water content in the studied mixtures at different ages

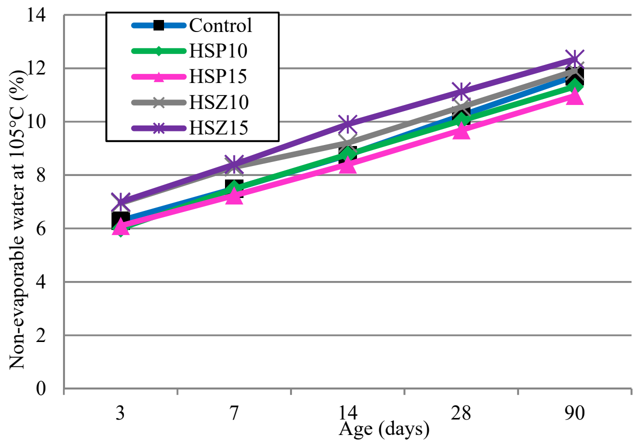

Fig. 8 Non- evaporable water content at 105 °C in the studied mixtures at different ages 3, 7, 14 and 90 days

- Pozzolanicity by Chapelle test

To evaluate the pozzolanic activity of the studied pumice and zeolite, the measurements based on modified Chapelle test was performed. Indeed, determining the amount of calcium hydroxide fixed by pumice and zeolite according to the modified Chapelle test is a method of assessment for its pozzolanic activity. In this test, 1 g of pozzolan with 2 g of CaO in the presence of 250 ml of water is reacted for 16 h at 90 °C. The uncombined lime is then dosed, and the result is expressed as milligrams of $Ca(OH)_2$ fixed per gram of pozzolan. The amount of $Ca(OH)_2$ fixed by pumice is found to be equal to 170 mg, and the one for zeolite is equal to 490 mg. This result shows a higher pozzolanic reaction of zeolite compared to pumice and is in a good agreement with those of non-evaporable measurements.

D. Durability Properties

- Water absorption and permeable voids

Absorption and permeability pore volume measurement was performed according to ASTM C 642-97. This determines by weighing; i) mass of a specimen concrete, ii) mass in the air (while still soaked in liquid), iii) mass in water and iv) dry mass. From these values, the water absorption, the percentage of absorption after immersion and boiling and the volume of permeable pore space (voids) in the hardened concrete are extracted. There are voids that communicate with the exterior surface of the concrete specimen or are interconnected with the surface. According to ASTM C642, permeable voids are considered as the voids that can absorb water when immersing concrete in water and boiling, or be emptied when drying it. The test was carried out after 7, 14, 28, 90, 180, and 365 days of curing in lime water on slices from cast cylinders with dimensions of 100×50 mm. Three samples by concrete formulation were tested. The test results of water absorption, absorption after immersion and boiling and void permeable are presented respectively in Figs. 9-11.

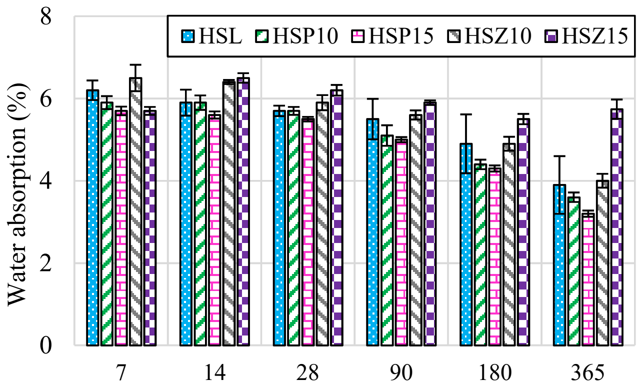

Fig. 9 Absorption after immersion (%) of studied HSSCCs

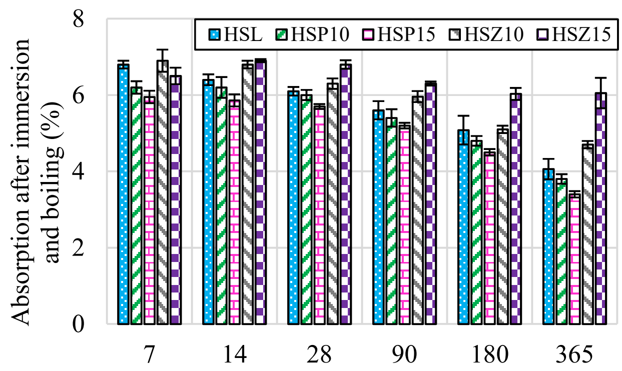

Fig. 10 Absorption after immersion and boiling (%) of studied HSSCCs

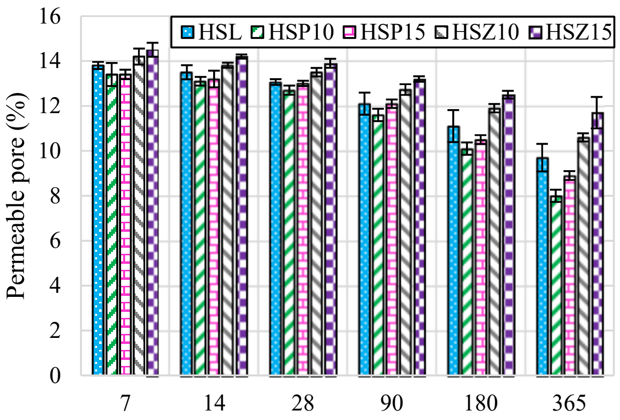

Fig. 11 Volume of permeable pore (voids) (%) of studied HSSCCs

The results indicated that using pumice instead of cement in concrete can reduce permeable pore, water absorption and absorption after immersion and boiling in comparison to control concrete. According to the results illustrated in Fig. 9, the water absorption in HSP10 is 1.03, 1.03, 1.04, 1.08, 1.14 and 1.16 times lower than the one of the control concrete at 7, 14, 28, 90, 180 and 365 days of aging respectively. Considering Fig. 10, the pumice pozzolan shows a positive effect on the results obtained by testing absorption after immersion and boiling when zeolite shows a negative effect. From the results shown in Fig. 10, the reducing trend in rate of absorption after immersion and boiling is very close to the results obtained for the water absorption. According to the result illustrated in Fig. 11, the HSSCC containing pumice shows good behavior in the reduction of the pore permeable rate compared to control concrete. Especially, this fact is more visible in the long term conservation. For concrete containing pumice, the reason can be found in the conversion of continuous pores to more discontinuous pores due to the pozzolanic reaction of this admixture. Its high content in alumina can contribute to the formation of additional hydration which can lead to lower connected porosity. However, concrete containing zeolite shows a completely opposite behavior. The amount of permeable pore in HSZ15 is greater than all the other formulations. The permeable pore for HSZ15 is 1.05, 1.05, 1.06, 1.09, 1.13 and 1.21 times higher than the one of the control concrete at the maturity of 7, 14, 28, 90, 180 and 365 days respectively. This behavior has a negative influence on the compressive strength. Indeed, the increased void content decreases the load carrying capacity of concrete and therefore, the compressive strength of HSZ10 and HSZ15 are decreased. According to these results, the amount of water absorption, absorption after immersion and boiling and permeable pore increases by increasing the additive level such as pumice and zeolite from 10% to 15% cement replacement. It is more visible in HSSCC containing zeolite. The consumption of higher amount of superplasticizer in mixtures containing zeolite has an effect on the compressive strength. Despite, the higher amount of non-evaporable water in paste with zeolite and its higher pozzolanic activity obtained with Chapelle test, the compressive strength of SCC with zeolite in this study is lower. There are two reasons for this; i) the highest amount of evaporable water and ii) the high consumption of superplasticizer to achieve the desired slump which ultimately leads to an increase of entrained air in concrete. This result is in agreement with the one of [4], the authors have found that increasing the percentage of replacement of zeolite, demand of superplasticizer and the amount of porosity increases and on the contrary compressive strength decreases. The three different properties studied here can be related to compressive strength as shown in Figs. 12-14. A liner equation seems describe correctly the evolution of permeable pore, absorption after immersion and boiling, water absorption with compressive strength. Compressive strength increases with the decrease of these properties.

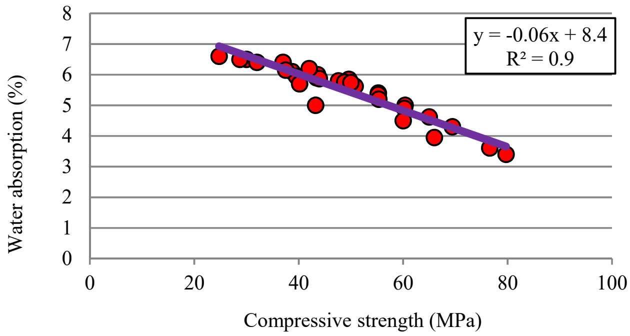

Fig. 12 Relationship between water absorption and compressive strength

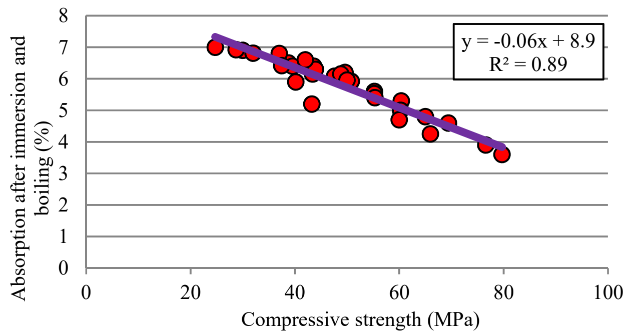

Fig. 13 Relationship between the absorption after immersion & boiling and compressive strength

- Capillary absorption (Sorptivity)

This test measures the rate of water absorption by capillary suction, brought into contact with water without external hydraulic pressure. Before the measurements of sorptivity, the specimens are preconditioned according to AFREM recommendations. The test was carried out on slices from cast cylinders with dimensions of 100×50 mm (three samples per formulation). Higher the capillary absorption, the greater the material is able to be quickly invaded by the liquid in contact. The coefficient of sorptivity (S) after 24 hours is measured for each formulation at different curing times (7, 14, 28, 90, 180 and 365 days). The results are given in Fig.15. Because capillary pores are gradually filled with water, with the progression of time during the test, capillary absorption coefficient is reduced. The beneficial effect on reducing capillary absorption compared to the control concrete is observed from 90 days of curing for HSSCCs containing pumice. Moreover, this reduction is more sensitive by increasing the percentage of natural pozzolan. According to these results, the performance of HSZ10 and HSZ15 in reduction of capillary absorption coefficient in all ages is far better than other mixtures. The value of sorptivity in HSZ15 after 24h of test for 7, 14, 28, 90, 180 and 365 days of curing are equal to 0.53, 0.48, 0.44, 0.41, 0.38 and 0.34 mm/h0.5 respectively. The great difference of sorptivity between the control concrete and mixtures containing pozzolan is obtained after 365 days of aging. HSL presents a difference 1.05, 1.13, 1.31 and 1.7 times higher than the one of HSP10, HSP15, HSZ10 and HSZ15 respectively. By comparing the results of different conservation ages, we can see the decrease in the value of sorptivity coefficients with progress in curing time.

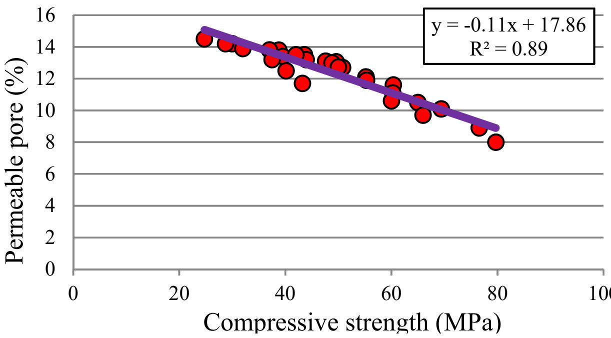

Fig. 14 Relationship between the volume of permeable pore and compressive strength

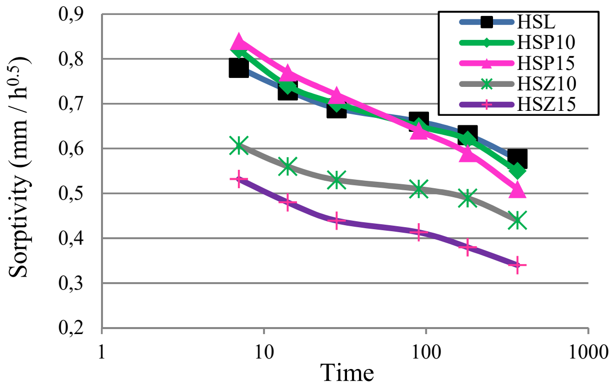

Fig. 15 Sorptivity coefficients of the studied HSSCCs at different curing ages (mm/h0.5)

The sorptivity may be reduced in long term due to the development of the pozzolanic reaction with time, which is also in agreement with the increasing of compressive strength. Fig. 16 presents the evolution of sorptivity with compressive strength. A liner relationship seems to link correctly these two properties. Sorptivity decreases with the increase of compressive strength. The correlation coefficients determined are 0.98 for HSL and HSZ15, 0.93 for HSP10 and 0.96 for HSP15 and HSZ10.

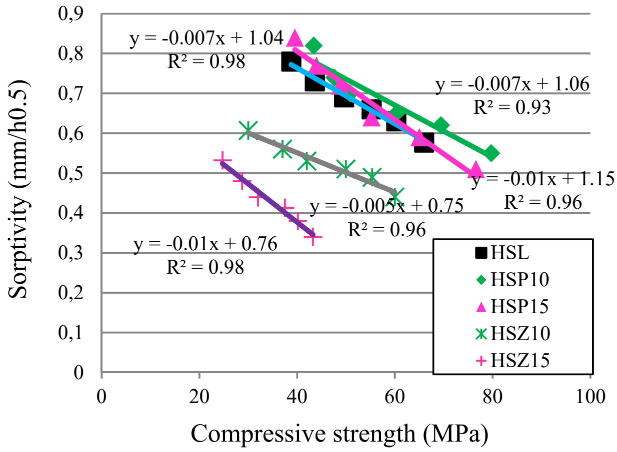

Fig. 16 Evaluation of sorptivity according to the compressive strength

- Water penetration

The rate of water penetration is a good parameter for comparing the permeability to water of concrete. The penetration of water in concrete can cause physical and chemical damage. Water as a solvent is able to dissolve many cementitious components. Many ions cause damage in concrete by the penetration of water in concrete. For this reason, the penetration of water in concrete can be used as an indicator in the study of concrete durability. This test was measured on three 150×150 mm cube specimens by applying water under a pressure of 0.5 MPa for 72h in accordance with BS EN 12390-8 (BSI, 2009). The results are presented in Fig. 17. As can be seen, replacing Portland cement with 10% and 15% of two types of pozzolan led to a reduction in the depth of penetration. The maximum and minimum depth of penetration of water in the studied HSSCCs after 28 days of curing corresponds to HSL and HSZ15 respectively. The water penetration depth of control mixture was 1.1, 1.25, 2.22, and 2.85 times higher than that of HSP10, HSP15, HSZ10, and HSZ15, respectively. According to this result, the mixture of HSZ15 shows the best behavior to the penetration of water among the mixtures studied.

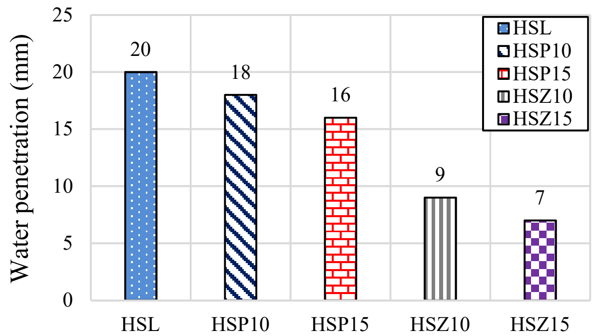

Fig. 17 Water penetration in the studied HSSCCs after 28 days of curing

VI. Conclusions

This study focuses on the effect of two different natural pozzolan (pumice and zeolite) on compressive strength and transport properties when used in high strength self-compacting concrete (HSSCC). The main results of this study are presented as follows:

1) Mineralogical and pozzolanic activity analyses have shown that the studied zeolite is a clinoptilolite that presents higher pozzolan activity compared to pumice. This last pozzolan contains glass materials, muscovite and anorthite minerals.
2) Pumice but more zeolite, enhances the viscosity and demand in superplasticizer; this demand increases with increasing the percentage replacement of pozzolan.
3) HSSCCs containing zeolite, despite the high pozzolanicity of this pozzolan, show high porosity and low compressive strength, fc, compared to control HSSCC. This is due to rheology problems related to the compatibility of the studied zeolite with some concrete components and in particular with the used superplasticizer. On the other hand, mixtures containing pumice exhibit at least comparable compressive strength to that of the control mixture. A significant increase in fc is observed at long term.
4) Zeolite improves sensitively the resistance of concrete to water both at early age and long term, whereas pumice pozzolan improves this resistance only at long term. Also, with increasing the percentage of pozzolan this improvement is more considerable.
5) Taking into account all the results, the partial substitution of OPC by 15% of pumice or 10% of zeolite is affordable for all aspects including economic and environmental issues. An improvement in the mixture design when using zeolite by the use of other type of superplasticizer should be an interesting way to maintain good durability properties without decreasing the mechanical strength.

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