Advances in Concrete Construction, *Vol. 8, No. 3 (2019) 225-237*
DOI: https://doi.org/10.12989/acc.2019.8.3.225

Experimental investigation on the effect of cementitious materials on fresh and mechanical properties of self-consolidating concrete

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(*Received July 8, 2019, Revised August 13, 2019, Accepted September 22, 2019*)

Abstract. Although applying self-consolidating concrete (SCC) in many modern structures is an inevitable fact, the high consumption of cement in its mixing designs has led to increased production costs and adverse environmental effects. In order to find economically viable sources with environmentally friendly features, natural pozzolan pumice and blast furnace slag in 10-50% of replacement binary designs have been investigated for experiments on the properties of fresh concrete, mechanical properties, and durability. As a natural pozzolan, pumice does not require advanced equipment to prepare for consumption and only needs to be powdered. Pumice has been the main focus of this research because of simple preparation. Also to validate the results, in addition to the control specimens of each design, fly ash as a known powder has been evaluated. Moreover, ternary mixes of pumice and silica fume were investigated to enhance the obtained results of binary mixes. It was concluded that pumice and slag powders indicated favorable performance in the high percentage of replacement.

Keywords: self-consolidating concrete; pumice powder; slag; silica fume; binary and ternary scheme

1. Introduction

The temperature rise has led researchers to consider beneficial approaches for reducing the greenhouse gas produced by industries. The high consumption of cement by SCC causes environmental problems such as air pollution or climate changes. Consequently, the cement productions are affected by self-consolidating concrete, which is developing around the world. Self- consolidating concrete was initially designed to eliminate the vibration phase and increase velocity in concrete by relying on its weight. However, problems such as detachment, severe viscosity reduction, adhesion, environmental pollution and economic viability have encouraged many researchers to find a suitable replacement for cement (Boukendakdji *et al.* 2012, Ameri *et al.* 2015, Jahandari 2015, Jahandari *et al.* 2017, Nosrati *et al.* 2018, Saberian *et al.* 2018, Jahandari *et al.* 2019, Vali *et al.* 2019). In order to find a relationship between mixing percentage with cement and water, pozzolan has been investigated through various studies in recent years. Pozzolan is defined by ASTM (C618) as a silica or silica material that is not self-adhesive but adheres to cement and water. This paper is aimed to find an appropriate replacement for cement, which causes a reduction in environmental pollution and increasing properties of fresh concrete, hardened concrete, and durability. Therefore, slag, silica fume, fly ash, pumice, and pozzolan were the ordinary replacements of cement which were investigated in previous studies. Moreover, reinforced concrete is one of the most useful productions in the construction and building industry which its flexural and compressive strength has been enhanced in comparison to plain concrete even in the creep and shrinkage. On the other hand, nowadays using synthetic and natural fibers to reinforce the concrete is a sustainable way to achieve reliable reinforced concrete. Generally, SCC has a significant potential to be reinforced with different fibers and polymers (Davis *et al.* 1937, Mehta 1998, Malhotra 1999, Young *et al.* 2002, Hwang *et al.* 2004, Antiohos *et al.* 2007, Khayat *et al.* 2008, Dehwah 2012, Abedini *et al.* 2017, Abedini *et al.* 2019, Li *et al.* 2019).

As a result, natural volcanic pumice powder, pozzolan properties, silica fume, fly ash, and slag are studied in this paper.

Pumice powder is obtained directly from natural volcanic pumice; therefore, neither chemical nor mineral additives are applied during the production process of

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http://www.techno-press.org/?journal=acc&subpage=7 ISSN: 2287-5301 (Print), 2287-531X (Online)

pumice. Pumice is a type of volcanic product mainly containing silica and alumina, with bubble-like components with a large inner surface (Manville *et al.* 1998). The strong durability and strength of pumice are the results of its physical and chemical properties. Moreover, the improving durability of concrete

Hossain (2005), and resistance against sulfate attacks are the advantages of Pumice (Hossain and Lachemi 2006). It also improves some of the mechanical properties of concrete, including its initial strength. It should be mentioned that concrete can be produced with higher strength and lower weight in comparison to the cement while providing high tolerance to concrete. Slag is a mineral product that is chemically similar to cement (Armaghani *et al.*). Furthermore, slag is divided into two main parts, including crystallized slag, and granulated blast furnace slag. Crystallized slag is produced in two ways of fast and slow cooling which is placed in the aggregate materials category because of its size. It is also used in some cases such as pavement construction. Granulated blast furnace slag is one of the fine aggregates used as a replacement for cement in concrete. The produced slag around the world is about 600 million tons, which the granulated blast furnace slag is about 430 million tons, and crystallized slag is around 170 million tons (Beggas and Zeghiche 2013). The advantages of slag include low heat produced during hydration, reliable performance, resistance against sulfate and acid attack, resistance to abrasion and corrosion, and affordable price (Armaghani *et al.*). On the other hand, environmental pollution due to the production of CO_2 is the disadvantage of slag, and this is more related to the quenching molten iron process, a by-product obtained for use in concrete, and therefore may be considered as an advantage. In the following content, for the sake of brevity, the slag is used instead of blast furnace slag. In the present study, ash was used as a valid reference in order to obtain a better understanding of the performance of two other powders, pumice, and slag, along with design control specimens. Pumice has been prioritized in this research due to the simple production process and its application in the environment. Also, its ternary mix designs with silica fume were evaluated to improve the resistance and durability parameters. Therefore, in this study, the binary mixes of fly ash, pumice and slag, and ternary mixes of pumice and silica fume were investigated in general. The performed experiments include the slump flow test, compressive strength test, and electrical resistance test. In this case, the use of self-consolidating concrete can be useful in steel-concrete composite structures as floor system or composite beams which have not been widely performed, besides one of the most cost-effective and fastest ways to verify and achieve the experimental studies is the artificial intelligence analysis which has widely used in other studies (Shariati 2008, Moghaddam *et al.* 2009, Arabnejad Khanouki *et al.* 2010, Shariati *et al.* 2010, Arabnejad Khanouki *et al.* 2011, Daie *et al.* 2011, Hamidian *et al.* 2011, Shariati *et al.* 2011, Shariati *et al.* 2011, Shariati *et al.* 2011, Shariati *et al.* 2011, Sinaei *et al.* 2011, Hamidian *et al.* 2012, Jalali *et al.* 2012, Shariati *et al.* 2012, Shariati *et al.* 2012, Shariati *et al.* 2012, Shariati *et al.* 2012, Shariati *et al.* 2012, Sinaei *et al.* 2012, Mohammadhassani *et al.* 2013, Mohammadhassani *et al.* 2013, Schumacher and Shariati 2013, Shariati 2013, Shariati *et al.* 2013, Mohammadhassani *et al.* 2014, Mohammadhassani *et al.* 2014, Mohammadhassani *et al.* 2014, Shariati 2014, Shariati *et al.* 2014, Shariati *et al.* 2014, Toghroli *et al.* 2014, Aghakhani *et al.* 2015, Bazzaz *et al.* 2015, Khorramian *et al.* 2015, Mohammadhassani *et al.* 2015, Shah *et al.* 2015, Shao and Vesel 2015, Shariati *et al.* 2015, Toghroli 2015, Arabnejad Khanouki *et al.* 2016, Fanaie *et al.* 2016, Khorramian *et al.* 2016, Mansouri *et al.* 2016, Safa *et al.* 2016, Shah *et al.* 2016, Shah *et al.* 2016, Shah *et al.* 2016, Shahabi *et al.* 2016, Shahabi *et al.* 2016, Shariati *et al.* 2016, Shariati *et al.* 2016, Shariati *et al.* 2016, Tahmasbi *et al.* 2016, Khorami *et al.* 2017, Khorami *et al.* 2017, Khorramian *et al.* 2017, Mansouri *et al.* 2017, Shariati *et al.* 2017, Toghroli *et al.* 2017, Chahnasir *et al.* 2018, Heydari and Shariati 2018, Ismail *et al.* 2018, Nosrati *et al.* 2018, Nosrati *et al.* 2018, Paknahad *et al.* 2018, Sadeghipour Chahnasir *et al.* 2018, Sari *et al.* 2018, Sedghi *et al.* 2018, Shao *et al.* 2018, Shariat *et al.* 2018, Shariati *et al.* 2018, Toghroli *et al.* 2018, Toghroli *et al.* 2018, Toghroli *et al.* 2018, Wei *et al.* 2018, Zandi *et al.* 2018, Ziaei-Nia *et al.* 2018, Chuanhua Xu 2019, Katebi *et al.* 2019, Milovancevic *et al.* 2019, Shao *et al.* 2019, Shariati *et al.* 2019, Shi *et al.* 2019, Shi *et al.* 2019, Suhatril *et al*. 2019, Trung *et al.* 2019).

In recent years, several experimental and numerical studies have been conducted to evaluate the SCC performance in composite constructions. In this regard, C-shaped shear connectors as the channel, angle, perforated, and even the pipe shear connectors showed an appropriate shear capacity and improved composite action while they were embedded in well prepared high strength concretes. Therefore, the SCC employing the connectors, as mentioned above, could be a reliable alternative for the concrete slabs in the floor systems and composite beams (Shariati *et al.* 2010, Shariati *et al.* 2011, Fanaie *et al.* 2012, Shariati *et al.* 2012, Shariati *et al.* 2012, Shariati 2013, Shariati *et al.* 2014, Khorramian *et al.* 2015, Khorramian *et al.* 2016, Shahabi *et al.* 2016, Shariati *et al.* 2016, Tahmasbi *et al.* 2016, Khorramian *et al.* 2017, Shariati *et al.* 2017, Hosseinpour *et al.* 2018, Nasrollahi *et al.* 2018, Wei *et al.* 2018, Shariati *et al*. 2019).

Besides, numerical methods can be used to predict and optimize the SCC properties obtained from the experimental results of previous studies on concrete and steel. Hence, the ANFIS evaluations were performed to analyze the experimental results of the performance of shear connectors. Also, it was found that either by artificial neural network or the artificial neuro-fuzzy inference systems, a series of analytical evaluations could be applied on experimental results. Also, other algorithms, such as extreme learning machine or hybrid computational systems, have been carried out in some cases. Therefore, the presented predicted or optimized results proved the authenticity of the algorithms above (Khorami *et al.* 2017, Sedghi *et al.* 2018, Shariat *et al.* 2018, Katebi *et al.* 2019, Luo *et al.* 2019, Shariati *et al.* 2019, Trung *et al.* 2019). Also, a new soft computing and intelligent algorithms approaches have been already performed on some experimental test results. Therefore, using a hybrid algorithm could be a wise decision in case of cost

Table 1 The chemical components of Portland cement and other cementitious materials

Components (%)	Cement	FA	Pumice	Slag	SF
SiO_2	22.42	62.8	44.13	33.1	86.2
Al_2O_3	4.68	45.9	16.71	13.8	1.44
Fe_2O_3	3.68	0.92	1.72	3.12	0.2
CaO	63.25	2.60	11.09	40.7	3.06
MgO	3.63	1.40	1.95	8.70	1.32
SO_3	1.74	0.49	0.39	0.60	0.34
Specific gravity (kg/m^3)	3160	2200	2850	2850	2350
Blaine (m^2/kg)	290	260	320	445	20000

FA: Fly ash, SF: Silica fume

management and time-saving (Hamdia *et al.* 2015, Le-Duc *et al.* 2016, Vo-Van *et al.* 2017).

Moreover, the thermal strength of the slabs has a direct influence on the shear capacity and performance of the composite beams in the floor systems at elevated temperatures, and hence, the thermal performance of slabs in composite structures can be improved by using SCC mixtures (Shahabi *et al.* 2016, Davoodnabi *et al.* 2019, Shariati *et al*. 2019).

Besides, there are various evaluations proposed to study the previous concrete containing the polymers, silica fumes, and rubber aggregates. It was reported that these combinations have higher compressive and flexural strength compared to mineral aggregates. Also, environmental concerns have led researchers to find a creative solution, which leads to decreasing pollutions and reducing the cost of concrete production. Consequently, applying waste materials such as tires, steel fibres, steel slags, and plastics could be an appropriate replacement for cement, which is utilized in Portland cement. In addition, concerning the requisite properties for pavement concrete, SCC could be an alternate for current concrete pavements (Toghroli *et al.* 2017, Bazzaz 2018, Toghroli *et al.* 2018, Li *et al.* 2019, Shariati *et al*. 2019).

According to the investigations which have been done on the beams, especially beams with high strength concrete, using the SCC could be an appropriate choice for engineers due to its workability and handy nature. Also, it was reported that applying silica fume and slag in a binary mixture can provide a high-quality SCC (Arabnejad Khanouki *et al.* 2011, Sinaei *et al.* 2011, Mohammadhassani *et al.* 2013, Mohammadhassani *et al.* 2014, Shah *et al.* 2016, Heydari and Shariati 2018, Xie *et al.* 2019).

Whereas the SCC showed an excellent electrical resistivity and appropriate chloride penetration along with the high compressive strength, it could be used as high-performance concrete in some cases. Also, the required compressive strength could be achieved by incorporation of additive powders as slag (Arabnejad Khanouki *et al.* 2010, Nosrati *et al.* 2018, Sajedi and Shariati 2019)

2. Experimental program

2.1 Materials

To conduct the experiments, a commercially available ASTM type II Portland cement with a specific density of 3160 kg/m^3 and fineness of 290 m^2/kg and volcanic pumice were applied.

The mixing coarse aggregates with a maximum size of 19 mm and a density of 2.5 kg/cm^3, and fine aggregates with Blain of 3.6, the specific density of 2.7 g/cm^3 and water absorption of 2.95% were considered to ensure the sufficient strength of natural aggregates. In order to achieve the desired performance and regulate the slump loss, the LG superplasticizer based on carboxylate with 1.07 g/cm^3 density and drinking water was employed. As previously mentioned, pozzolan pumice, slag, fly ash, and silica fume

Table 2 Mix proportion of self-consolidating concrete

Cement material	(kg/m^3) Pumice	Silica fume	Slag	Fly ash	Cement	(kg/m^3) aggregate		(kg/m^3) water
						gravel	sand	
Control	0	0	0	0	500	1070	580	191
FA10	-	-	-	50	450	1063	590	191
FA20	-	-	-	100	400	1052	584	191
FA30	-	-	-	150	350	1040	578	191
FA40	-	-	-	200	300	1029	571	191
FA50	-	-	-	250	250	1017	565	191
Pu10	50	-	-	-	450	1072	595	191
Pu20	100	-	-	-	400	1069	594	191
Pu30	150	-	-	-	350	1066	592	191
Pu40	200	-	-	-	300	1063	590	191
Pu50	250	-	-	-	250	1060	589	191
Slg10	-	-	50	-	450	1072	595	191
Slg20	-	-	100	-	400	1069	594	191
Slg30	-	-	150	-	350	1066	592	191
Slg40	-	-	200	-	300	1063	590	191
Slg50	-	-	250	-	250	1069	580	191
Pu25- SF5	125	25	-	-	350	1063	590	191
Pu45- SF5	225	25	-	-	250	1057	587	191
Pu40- SF10	250	50	-	-	200	1051	584	191

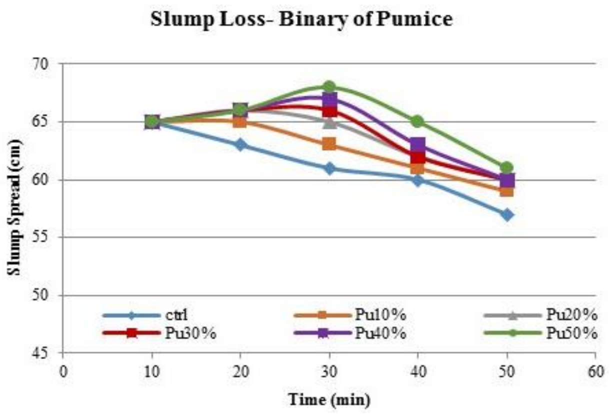

Fig. 1 Slump loss of binary pumice during the 50 minutes

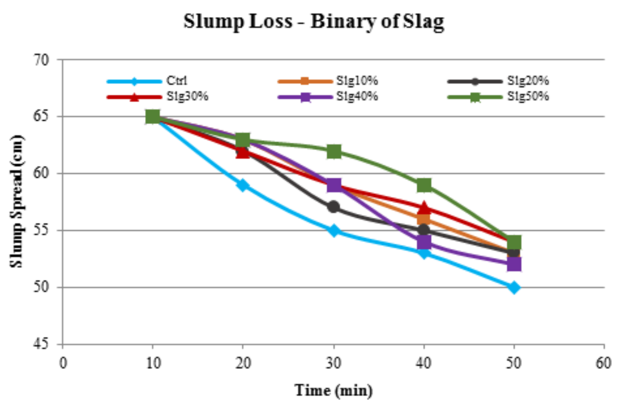

Fig. 2 Slump loss of binary slag during the 50 minutes

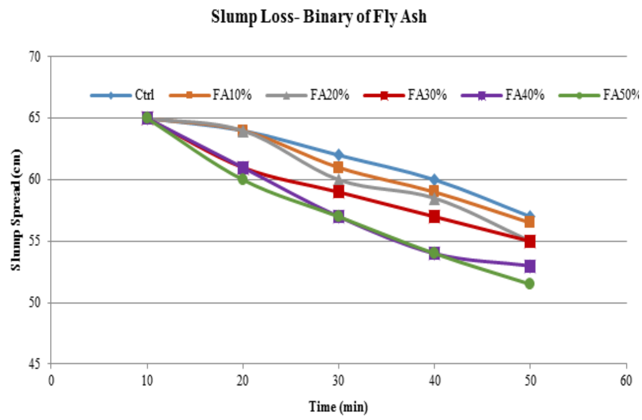

Fig. 3 Slump loss of binary fly ash during the 50 minutes

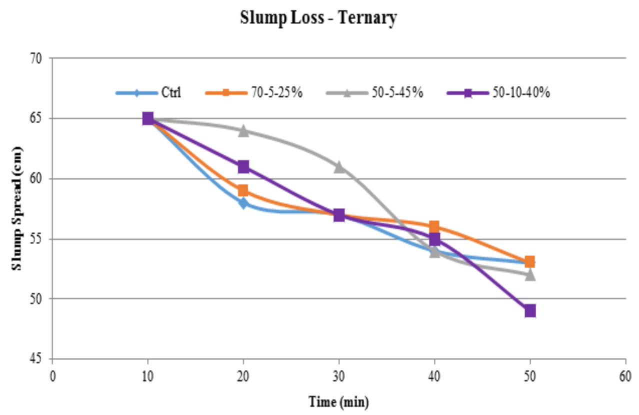

Fig. 4 Slump loss of ternary mixes pumice and silica fume during the 50 minutes

are the cement alternatives with different replacement percentages that are used with binary and ternary mixtures. Table 1 indicates the specific density and chemical components of the cement.

2.2 Mix proportion

In the first series of mix designs, the fly ash, pumice, and slag binaries with 10, 20, 30, 40 and 50 % replacement and water to cement ratio 38% were considered. The ternary mixtures of pumice and silica fume with the same water to cement ratio were used in the second series, which are shown in Table 2. The cementitious material content in all designs is 500 kg/m^2. In addition, the replacement percentage of materials was shown by the name of each design. At first, the dry materials were mixed, and then water and superplasticizer were added. The mixing process was about 10 minutes, and concrete rested for about four minutes after the first three minutes, and then it was mixed in the machine in three minutes. After 10 minutes, the slump flow test was performed immediately.

2.3 Tests

The 12 standard cube specimens with a size of 15×15×15 cm were used in each series of mixing designs. These specimens were molded 24h under laboratory condition after mixing process and applied in water tanks at an average temperature of 20°C. To determine the workability of fresh concrete in SCC at different intervals, the slump flow (according to ASTM C1611) was evaluated, which measures the concrete propagation after the funnel removal. The degree of filling ability and SCC stability were obtained by the results of the slump flow experiment. According to ASTM C39, the results of compressive strength were collected at 7, 28, and 90 days after mixing.

3. Experimental results

3.1 Fresh concrete properties:

3.1.1 Slump flow measurement

Figs. 2-4 shows the slump flow measurements in the range of 10 to 50 minutes. As the replacement percentage increases, the slump flow loss decreases in the binary mixes of slag and pumice. Figs. 1 and 2 show the descending curve trends of pumice and slag, which are completely different. In the 30th minute, the growing trend of slump flow measurement and replacement percentage of more than 20% can be seen in the mixture. In order to improve the accuracy and approval of measurements, the experiment was repeated for more than four times for different percentages. The growing trend of slump flow results in creating the bell-curved, and it should be related to the physical properties of pumice particles. It appears that

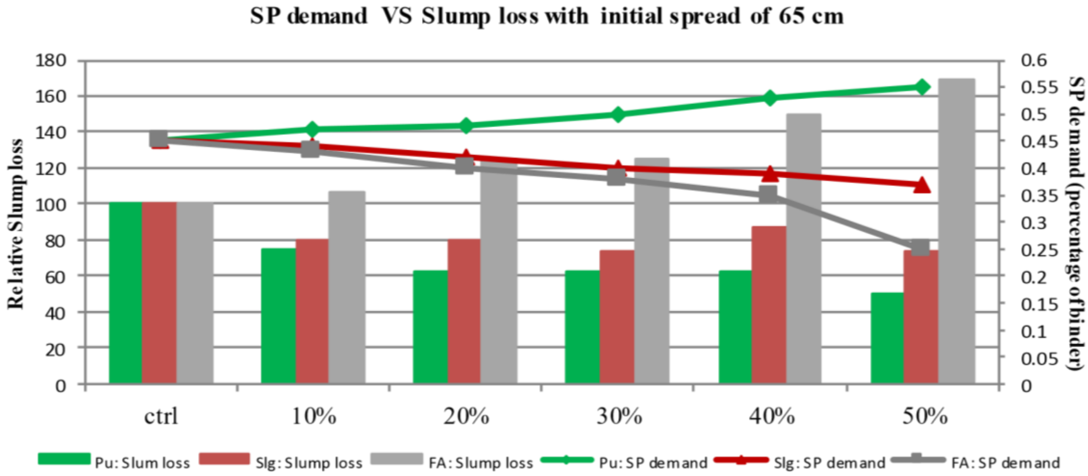

Fig. 5 Superplasticizer consumption and slump flow loss in the range of 10-50 minutes for binary designs

pumice particles can absorb the mixed water in the initial minutes, and then the absorbed water is returned to the mixture which leads to increasing water to cement ratio and its fluidity in the middle minutes. Then the cement paste enters its normal phase and again slowdowns the slump flow. Also, the mixture should be stirred for 20 seconds before each experiment.

Slag has a lower paste viscosity, and its glass crystalline particles absorb less water-soluble in comparison to pumice. Hence, the mixture of slump flow is high spontaneously in the early minutes, which increases with rising slag replacement. Fig. 3 indicates that ash has shown different results in contrast to the binary of slag and pumice. As the fly ash replacement increases, the slump loss also increases. This trend could be related to the fine particles of fly ash in comparison with the size of cement, pumice, and slag aggregates, which provide more surface and lead to the higher friction between particles. Fig. 5 shows the increasing trend of slump flow, which continues by adding silica fume on the ternary of pumice and silica fume. Silica fume has the smallest particle size among all the powders, and with a surface area of 2000 kg/m^2. Therefore, as can be seen in Fig. 4, increasing the replacement value results in the further slump flow drop. The results in the 30th minute showed that the presence of pumice with the growing trend of slump flow could overcome the slump flow loss induced by silica fume, and in all specimens, the slump flow should not be lower than the initial control specimen.

3.1.2 Superplasticizer consumption

Fig. 5 shows a comparison of superplasticizer demand and slump loss between 10-50 minutes for all binaries. To better analyzing, all slump drops were converted to the relative numbers. Control specimen of each binary was supposed as 100%, and other designs were proportioned based on own specimens. Furthermore, to achieve the slump of 65±2, the amount of superplasticizer was determined in the 10th minute. According to the results, more superplasticizer was consumed by binary mixes of pumice to achieve a slump of 65±2, which had a lower slump loss. Increasing replacement percentage resulted in lower consumption of superplasticizer.

The slag particles at the mixing process onset had small water absorption, which makes the behavior of the mixture very sensitive to superplasticizer. Therefore, concrete segregation is caused by adding a small amount of superplasticizer, which is more than the usual content. Generally, due to the superplasticizer consumption and the reasonable slump loss, it appears that slag had better performance than the other two powders. On the contrary, because of the spherical shape of the fly ash particles which results in decreasing intergranular fraction and improving mixture fluidity, fly ash had the least superplasticizer demand and the highest slump loss. Also, the shorter preservation of slump flow is achieved due to the lower consumption of superplasticizer (Ramachandran and Malhotra 1996, Shi *et al.* 2004). Additionally, the curing period is reduced by high alumina oxide (45.9%) of fly ash, which leads to faster slump flow loss. This value is much lower for pumice and slag powder which was approved by obtained results.

Results showed that for a single slump flow, more superplasticizer was consumed by pumice in comparison to the other two powders. Superplasticizer also increases with increasing replacement but results in less slump flow. On the other hand, adding silica fume to the mixture led to slump loss over time, which did not have a considerable effect on the initial slump and amount of initial superplasticizer used. Therefore, in the ternary mixes of pumice and silica fume, a mixture containing pumice with a higher percentage of replacement needs more superplasticizer. However, its slump is reduced, and the different results are obtained by the mixture containing more silica fume. The conformity of these statements with obtained results is shown in Fig. 6.

According to the results, the inverse relationship between the amount of superplasticizer demand and the slump flow loss is obvious, and hence, as the superplasticizer demand decreases, the higher slump loss is obtained. It was also found that in binary designs, the 30% of replacement for pumice and slag is quite affordable and acceptable. In terms of ternary designs, 45% pumice replacement along with 5% silica fume could be propitious to the design demand.

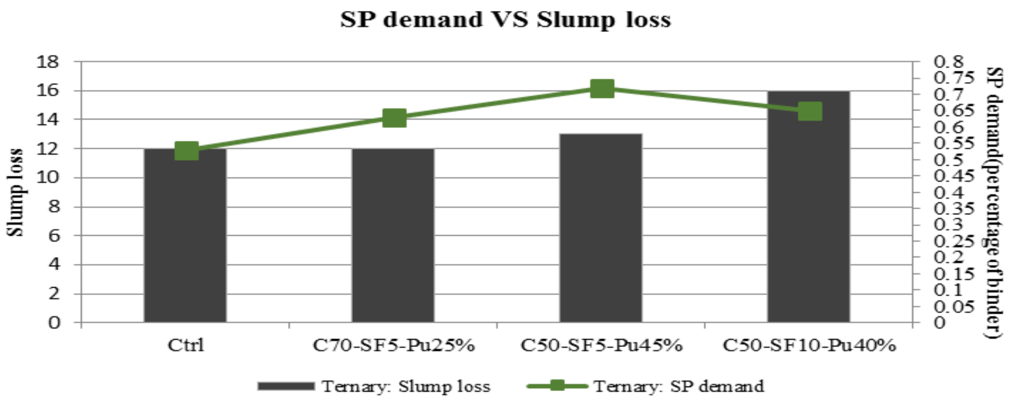

Fig. 6 Superplasticizer consumption and slump flow loss in the range of 10-50 minutes for ternary designs

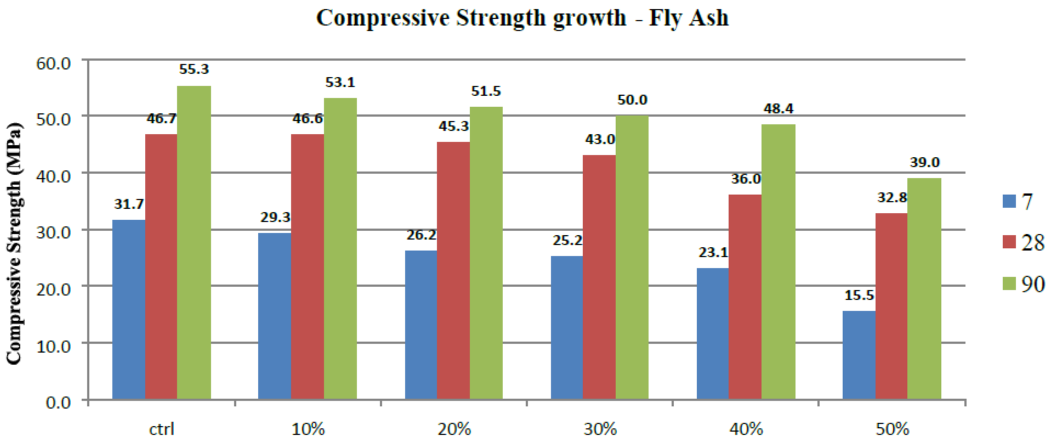

Fig. 7 compressive strength of fly ash binaries

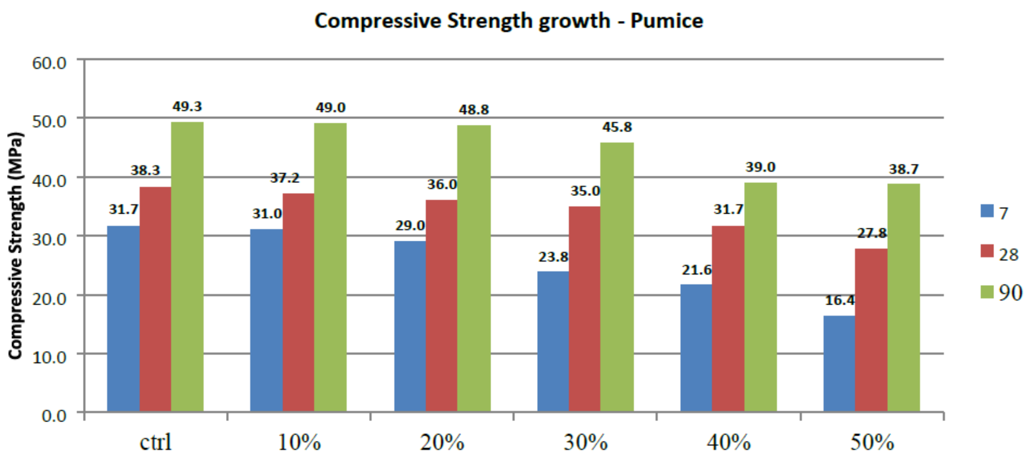

Fig. 8 compressive strength of pumice binaries

3.2 Mechanical properties of SCC

There are various standards to apply fly ash as a replacement for cement, such as ASTM C618, which classifies fly ash according to its components. Consequently, in order to make a more reliable comparison, fly ash has been chosen as an appropriate reference among the pozzolanic materials along with the control specimen. The results showed that as the replacement percentage of fly ash increases, the compressive strength decreases. Fig. 7 shows that the 14 Mpa of strength loss was obtained by replacement between 0 and 50% at the age of 28 days. Although the descending curve is not linear, the reduction value is constant up to 30%, and then a sharp drop occurs due to the reaction of fly ash with $Ca(OH)_2$ in the concrete paste and forming adherent components. The Ca(OH)2 is a byproduct of the reaction between C3S and H2O. As the amount of $Ca(OH)_2$ depends on the cement value, increasing the replacement of fly ash results in increasing mechanical properties of concrete and decreasing the $Ca(OH)_2$. It was found that $Ca(OH)_2$ was sufficiently present in the concrete paste up to 30% of replacement,

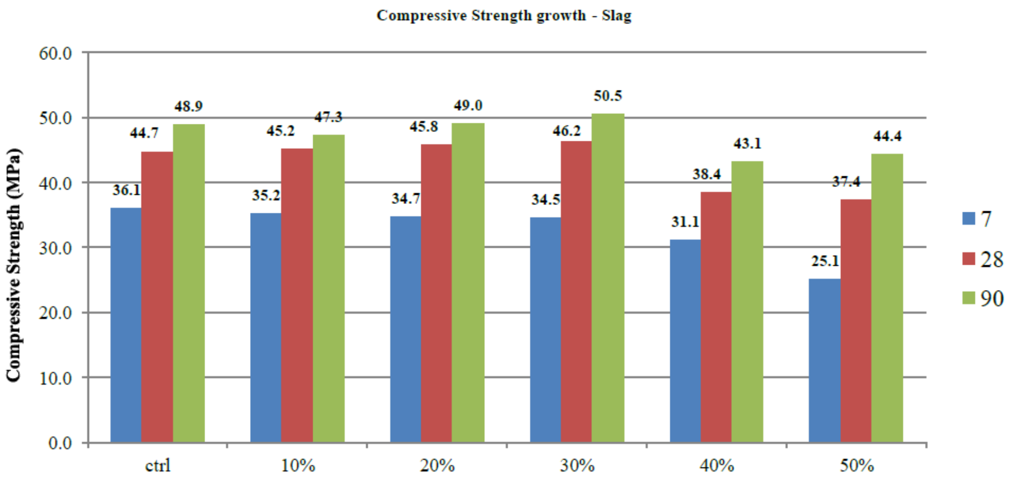

Fig. 9 Compressive strength of slag binaries

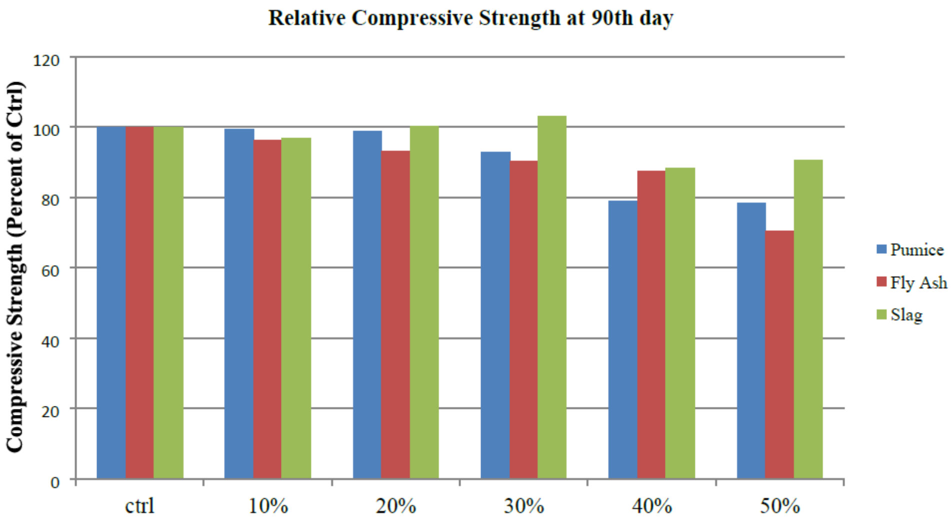

Fig. 10 90-day relative strength of binary designs

while 10% extra fly ash causes dissipating $Ca(OH)_2$ and thus results in a sudden drop in compressive strength. The more strength in the binary mixtures is expected to be observed with the creation of more lime over time. As shown in Fig. 7, the compressive strength of binary mixtures in older ages approaches its control specimen.

Fig. 8 indicates the compressive strength of binary mixes of pumice at 7, 28, and 90-day. As the pumice decreases the compressive strength and replacement percentage increases similar to the fly ash. The difference between 0, 10, and 20% replacements was not observed in 90 days. This trend is also valid for shorter days. There is no significant difference even with a 30% replacement. Finally, the strength loss during the 50% of replacement is about 10.5 MPa, which is relatively less than the measured value for fly ash. In terms of the compressive strength of concrete, it is clear that pumice performance is more efficient than fly ash.

The hardening time of concrete is delayed by using pozzolan (except silica fume) unless they indicate high adhesion properties like cement. The pozzolanic activity cannot occur earlier than cement hydration reactions, and hence the delay in hardening is achieved. This fact is approved by the slag presence in the binary mixes. However, slag is more similar to cement in terms of the components and hence has a higher rate of compressive strength compared to pumice and fly ash, as seen in Fig. 9. The graph in Fig. 12 also reveals that 10, 20 and 30% of replacement is approximately equal to the control specimen and the value of compressive strength loss for the 50% specimen is about 7.3 Mpa which is much lower than the obtained results for other two powders.

In order to compare all three groups in a diagram, the results of 90-day compressive strengths were converted to relative percentages, as seen in Fig. 10. All control specimens were considered as 100%, and other designs were assigned a percentage proportional to their control specimen. The most significant effect on the improvement of compressive strength is caused by slag, and this should be due to the larger surface area of its particles, which provides more space for OH- and alkaline ions to penetrate the pores of the paste (Li and Zhao 2003).

The high amount of SiO_2 and CaO is another reason for the strength development, which are constitutions of slag and as long as these two components are responsible for the mechanical properties of the concrete paste, the

Table 3 proportion of incorporation plan

Cementitious material	Pumice	Silica fume
Control 1	0	0
Pu25- SF5	25	5
Pu45- SF5	45	5
Pu40-SF10	40	10

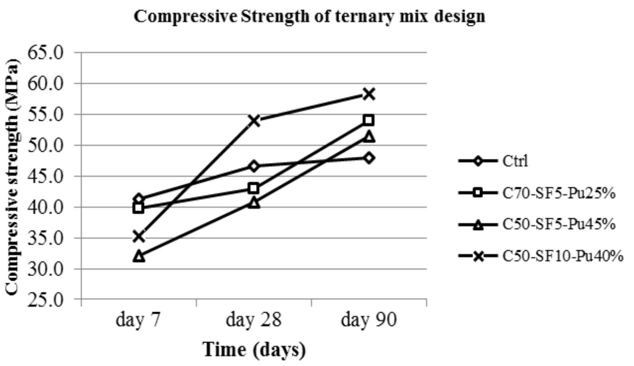

Fig. 11 The compressive strength of ternary designs in 7, 28, and 90 days

compressive strength of slag is higher than pumice and fly ash. The high percentage replacements result of binaries indicated that additional material is required to increase the compressive strength, especially at younger ages. Thus, ternary of pumice with silica fume was studied in three different ratios, where the silica fume enhances the compressive strength and durability of concrete. The mix designs ratio and results of 3, 28, and 90-day compressive strength are shown in Table 3 and Fig. 11, respectively.

At the early ages, Pu45 and control specimen are in the lowest and highest strength level, respectively. While the control results of Pu45 and Pu25 are close to 28 days of age, Pu40 increased steeply and showed high resistance at middle ages. Finally, the control specimen showed the lowest resistance among others in 90 days. There are several studies indicate that the growth of compressive strength can be accelerated by 2.5-10% replacement of silica fume (Shariati *et al.*, Shariati *et al.*, Chen *et al.*, Ghassemieh and Bahadori 2015, Zhao *et al.*). It is attributed to the filling role of silica granules as well as the effect of silica fume on strengthening the weak layer between paste and aggregates. On the other hand, based on the results of the previous section, a high amount replacement of pumice leads to reducing the compressive strength at least under 90 days of age. Therefore, the result of the ternary designs in the early ages indicated that the silica fume additive effect would not be able to overcome the pumice reducing impact, and the resistance of all specimens is less than the control specimen strength. The availability of more lime has led silica fume to have better performance. Also, the compressive strength of all specimens would be higher than control ones by reinforcing the interfacial transition zone (ITZ) layer. This resistance growth is quite desirable to the authors as satisfies the purpose of the study. Small amounts of silica fume could be combined with high percentages of pumice, and as the results confirm, the compressive strength is at an acceptable level.

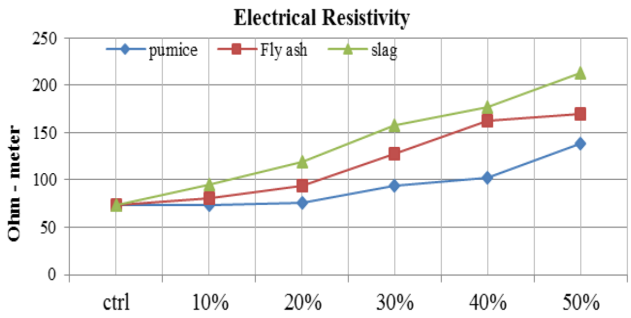

Fig. 12 The electrical resistivity of binary mixes

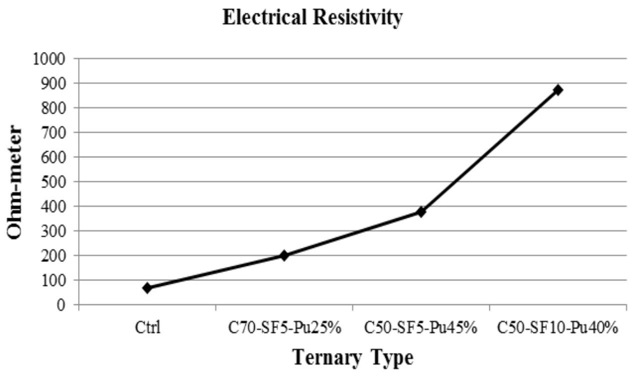

Fig. 13 The electrical resistivity of ternary mixes

3.3 The durability properties of SCC-Electrical resistivity

Figs. 12 and 13 show the electrical resistivity of binaries and ternaries which evaluate the durability of SCC. In all binaries and ternaries, increasing replacement percentage of pozzolan instead of cement leads to rising electrical resistivity. However, the increased amount for all three powders is not the same. Based on the binary results, slag and pumice had the highest and lowest effect on increasing electrical resistivity, respectively. The $Ca(OH)_2$ consumption by pozzolan, causes paste matrix grid to be denser and prevents its carbonation. Hence, pozzolans mainly increase electrical resistivity. Also, the mixture of pumice and silica fume leads to the highest growth in electrical resistivity. In addition to the mentioned reasons, reducing the cavities volume and increasing the cohesion between the cement-aggregates paste are the factors contributing to this growth (Cheng-Yi and Feldman 1985, Cohen 1990).

4. Conclusions

The use of binary mix designs in comparison to the ternary designs in SCC has the advantage of simple preparation, and hence, it is expected that the binaries will be used more frequently. Since finding a cheap powder with the least impact on the environment is a priority for concrete industry researchers, in this study, different replacement percentages for powders were introduced in the form of the fresh concrete tests, mechanical properties test, and durability evaluation.

The obtained results of the fresh SCC showed that pumice in the 30th min after mixing leads to increasing trend during slump flow, which has a significant effect on the preservation of optimal slump and SCC efficiency. The increasing trend of slump flow is related to the physical properties of pumice. It seems that pumice particles are capable of adsorbing water in the first few minutes and, over time, returning the adsorbed water to the mixture, which causes an increment in water to cement ratio and its fluidity in the middle minutes.

Although superplasticizer consumption of pumice powder is more than the other two powders, its advantages can easily justify these differences. Low prices, non-destructive effects on the environment and simple preparation process, make pumice a valuable powder for developing binary designs.

The slag binary blends of SCC give rise to measuring a moderate slump flow drop and superplasticizer consumption compared to the other two powders. As long as the slag is a by-product of the steel industry, its consumption according to the obtained results is undoubtedly cost-effective. However, it should be considered that slag due to the crystallinity of its particles and the low viscosity of the resulting mixture is very sensitive to superplasticizer, and adding a little more than the desired amount can quickly lead to disintegrating and segregating the SCC. Therefore, there are more precision and experience required for slag compared to the pumice in the mixing process.

Although mixing of the ternaries ratios is more complex and requires more careful management by the supervising engineer, the results have shown that the ternaries have much more enhanced properties than the binaries. Due to the appropriate properties of pumice and desirable capability with the high replacement percentages in binaries, ternaries have also been investigated with silica fume. Results show that 45% replacement of pumice and 5% silica fume by cement is affordable and this could be decisive in supplying optimum ratio.

The compressive strength of binary designs and the replacement of 0-30% indicate that slag and pumice have similar results with the control specimen, which provide a favorable effect on compressive strength compared to fly ash. Also, in replacements of more than 30%, slag has faster growth.

The compressive strength of the specimens in the ternary designs by adding 5-10% of silica fume reached more than 40 MPa at the age of 28 days, which is favorable to internal standards. Also at the age of 90 days, all specimens were higher than the control ones. Thus, in the ternary designs, the replacement of 45% pumice and 5% silica fume is considered, which exhibits better properties than the control sample with high replacement volume.

Electrical resistance results of the specimens showed that all three pozzolans had a better performance than the control. Although this effect is highest in slag and lowest in pumice, it does reduce the permeability of the harmful ions. Since pumice had the least effect compared to the other two powders, its binary composition was tested with silica fume, which significantly increased the electrical resistance.

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