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RESEARCH PAPER

Investigating the Effects of Copper Slag and Silica Fume on Durability, Strength, and Workability of Concrete

Ravanbakhsh Shirdam[1] · Mahdiyeh Amini[1] · Nematollah Bakhshi[2]

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Abstract

Workability, strength, durability, economic considerations, and attention to sustainable development issues are some crucial factors in designing an appropriate mix. The use of copper slag as a partial replacement of cement is an effective method of pollution reduction and conservation of resources, since it reduces cement use. In addition, silica fume is used in combination with copper slag to make concrete structures more durable. The main purpose of this study was optimizing important variables of concrete mix design including cement factor, water-to-binder ratio (*w*/*b*), copper slag, and silica fume to improve concrete durability. To achieve this goal, an experimental research was carried out, based on standards, to optimize changes in the said fields. Concrete durability is determined by experiments considering electrical resistance of concrete, bulk electrical conductivity, and chloride migration coefficient. Interfacial transition zone and cement microstructure were evaluated using X-ray analysis and scanning electron microscopy. The results of this research indicated that simultaneous use of copper slag and silica fume with appropriate values of other factors (cement factor and *w*/*b* ratio) yields a more durable, workable and strengthened mix design. The optimized mix introduced a workable, durable, resistant, and economical mix design with 7% and 20% of cement replaced with silica fume and copper slag, respectively. This innovative study included simultaneous use of copper slag and silica fume as a replacement for cement.

Keywords Copper slag · Silica fume · Permeability · Durability · Strength · Workability

Introduction

Concrete protection management is needed to extend structure life and reduce maintenance costs (Kumar Mehta and Monteiro 2002). Copper slag is a waste product of smelting and refining process of copper production (Shi et al. 2008). 2.2–3 tons of slag is produced per one ton of copper (Taher Shamsy et al. 2011). Proper management of copper slag as a by-product of copper production, which contains oxides such as Fe_2O_3, SiO_2, and Al_2O_3, is economically justifiable.

Copper slag is a waste of flash furnace (Mohsenian and Sohrabi 2011). Copper slag hardness is 6–7 Mohs, and is hard to grind. Copper slag is used in various industries such as construction projects (cement, concrete), road projects (in different sectors of infrastructure and road pavement), as well as in the manufacture of concrete and asphalt surfaces.

Sobhani et al. (2012) considered durability and corrosion of copper slag and zeolite containing concrete with the use of impedance electrical circuit. The results indicated improved durability and reduced corrosion. Copper slag can be used in producing high-workability mortar as a partial replacement for cement. Pozzolanic activity depends on temperature, curing age, and fineness of slag (Edwin et al. 2016).

The compressive strength of 70 MPa and flexural strength of 6 MPa were achieved with copper slag and fly ash in Geetha's investigation (Geetha and Madhavan 2017). Brindha and Nagan (2010) used copper slag as a replacement for 20% and 60% of cement and aggregate, respectively. Replacement of 15% and 40% of cement and aggregate, respectively, with copper slag increased concrete compressive and tensile strength, reduced the permeability of concrete, but it did not yield successful results in corrosion testing and sulfate attack. Replacement of cement with copper slag in amounts of 0%, 5%, 10%, 15%, and 20% led to an increase in the

✉ Ravanbakhsh Shirdam
r_shirdam@uoe.ir; Shirdamr@yahoo.fr

[1] Department of Environmental Engineering, College of Environment, Karaj, Iran

[2] Mineral Industries Research Center, Shahid Bahonar University of Kerman, Kerman, Iran

surface resistance against sulfate ions (Najimi et al. 2011). In Al-Jabri et al.'s investigation (2006), compressive strength was almost identical to that of the control sample. Appropriate results were not registered for modulus of elasticity. As slag increased to more than 13.5%, compressive strength was reduced. Compressive strength of concrete containing copper slag can be increased at a longer curing age. Due to reduced hydration temperature, the use of copper slag would be favorable for warm regions (Nazer Amin et al. 2012).

Onuaguluchi and Eren (2012) replaced cement with copper slag in amounts of 5%, 10%, and 15%, which resulted in improvement in the test of autoclave, reduced resistance to sulfate attack, increased resistance to penetration of chloride and acid attack, and finally improved concrete durability.

Silica fume enhances durability of concrete against aggressive agents (Wang et al. 2017). Water–cement ratio, cement factor, and type of cement are effective factors in the durability of concrete against corrosion (Azari et al. 1993). The use of silica fume at the levels of 0%, 5%, 10%, 15%, and 20% as replacement for cement has been reported. Compressive strength has also been reported to improve at the age of 7 and 28 days. The replacement of 10% silica fume for cement appears to be the best choice (Raveendran et al. 2015). Anbarasan examined the use of silica fume and metakaolin as a replacement for cement. An optimum combination of (35%, 15%) mass of cement by silica fume and Metakaolin, respectively, tend to increase the strength and durability of concrete compared with conventional concrete (Anbarasan and Venkatesan 2015). Properties of each material as a partial replacement of cement must match the inserted profile in ASTM C618-03 (2008). X-ray analysis can help to identify the potential of slag as a replacement for cement (Parhizkar et al. 2010). As the use of silica fume can improve the durability of concrete due to its high pozzolanic activity, the simultaneous use of silica fume with copper slag which its pozzolanic activity is almost moderate and can yield good results.

The results of experiments concerning electrical resistance of concrete, bulk electrical conductivity, chloride migration coefficient, slump, compressive strength, and water absorption provided the grounds for examining related factors to study quality performance and durability of concrete.

Materials and Methods

Used Materials

Copper Slag

In this study, the copper slag of Khatoon Abad was used as the partial replacement for cement. For this purpose, copper slag was transported to Concrete Laboratory from the depot in the factory. The slag was glassy and shiny. The stiffness of utilized copper slag was about 7 months with the average density of 3.5.

Cement

The cement used in this study was Type II of Portland cement, in accordance with the ASTM C150 (2012) standard, and was purchased from Abyek cement factory.

Silica Fume and Superplasticizer

In this study, silica fume and superplasticizer were provided by a construction chemical company. The superplasticizer can reduce water requirement to 35%. The results of X-ray analysis of the used materials are presented in Table 1 and Fig. 1.

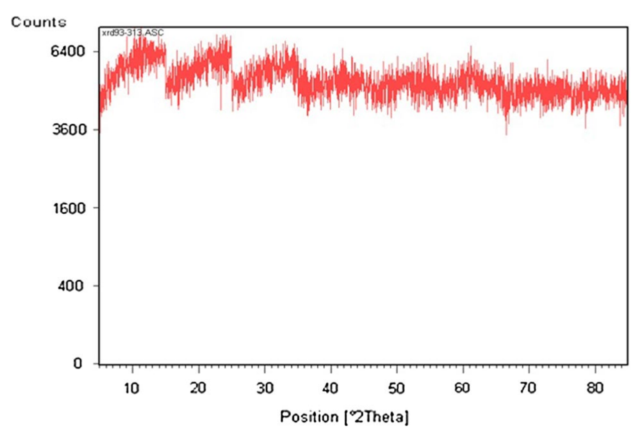

Fig. 1 X-ray diffract ion of the copper slag

Table 1 Chemical composition of cement, copper slag, and silica fume

	SiO_2	SO_3	MgO	Fe_2O_3	CaO	Al_2O_3	Another compounds
Compound/property (%)							
Cement	21.1	2	–	3.9	65	5.2	2.8
Silica fume	95.85	–	0.1–0.9	2–4	–	0.5–1.7	–
Copper slag	30.79	–	0.96	39.52	0.53	6.1	

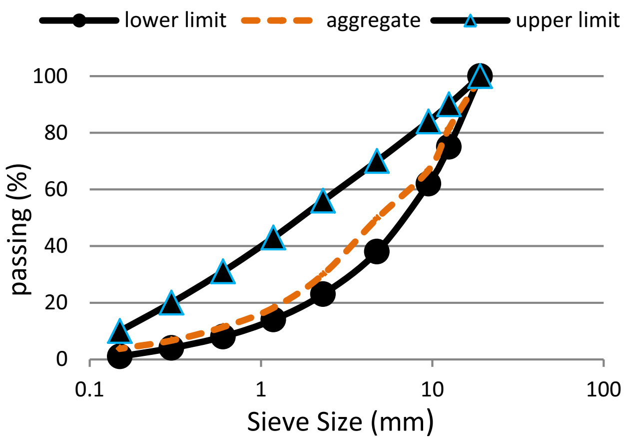

Fig. 2 Gradation of used aggregate in mix design

Table 2 Limits of studied variables

Variables	Lower limit	Upper limit
Cement factor (kg)	375	425
w/*b* ratio	0.4	0.5
Copper slag (%)	0	20
Silica flume (%)	0	7

Aggregate

The sand (0.075–4.75 mm in size and including 50% crushed sand) was used as fine aggregate, with a gravity of 2700 kg/m^3. The natural crushed stones (4.75–19 mm in size) were utilized as coarse aggregates, with a gravity of 2750 kg/m^3. Water absorption of fine and coarse aggregate was 2.4% and 2%, respectively. Aggregate gradation chart and accordance with national mix design's suggested values are reported in Fig. 2.

Design of Experiment and Mix Design of Concrete Samples

This experiment intended to optimize four key variables (copper slag, silica fume, cement factor, and *w*/*b* ratio). Table 2 shows the range of each variable. Nine tests were designed for the four variables. The mix design of concrete is presented in Table 3.

Chemical Analysis

Pozzolanic Characterization of Copper Slag

Table 4, according to ASTM C618, provides the chemical and physical requirements and specifications of fly ash and natural pozzolan as a supplementary cementitious material. Therefore, the XRF analysis of copper slag and LOI was conducted to determine chemical specifications and conduct physical analysis.

The mineralogical compounds of this slag were identified through XRD analysis shown in Fig. 1. As it is seen, not all main components can be identified. Thus, the copper slag is amorphous.

Specifications of Concrete Samples

- Workability and compressive strength.

According to ASTM C39 (1999), the cubic specimens ($10 \times 10 \times 10$ cm^3) were tested to evaluate the compressive strength at the age of 7, 28, and 90 days. Specimens were cured in a curing room at a temperature of 20 ± 2 °C. The slump test evaluated the workability of samples according to ASTM C143 (2015).

Table 3 Concrete mix design examples

Sample number	*w*/*b*	Adhesive material (kg)	Fine aggregate (kg)	Cement (kg)	Copper slag (kg)	Silica fume (kg)	Coarse aggregate (kg)	Super-plasticizer (kg)
1	0.5	425	1003	425	0	0	723	0
2	0.5	375	1064	348.75	0	26.25	766	0
3	0.4	425	1067	395.25	0	29.75	770	1
4	0.5	425	1072	300	75	0	775	0
5	0.4	425	1075	340	85	0	778	1
6	0.4	375	1128	273.75	75	26.25	816	1.6
7	0.45	400	1068	346	40	14	772	0.6
8	0.4	375	1123	375	0	0	813	1.6
9	0.5	425	1087	310.25	85	29.75	729	0

Table 4 Requirements of copper slag according to ASTM C618

	Specifications	The range	Copper slag
Chemical requirements	Sulfur trioxide (SO_3) (%)	Max, 4.0	0.72
	Chloride (%)	Max, 0.1	0.09
	MgO (%)	Max, 5	1–5
	Loss on ignition (%)	Max, 10.0	0.3
	$SiO_2+Al_2O_3+Fe_2O_3$ (%)	Min, 70	76
Physical requirements	Moisture content (%)	Max, 3.0	0
	Amount retained when wet-sieved on 45 µm sieve (%)	Max, 34	40
	Strength activity index, at 7 days, percent of control (%)	Min, 75	75
	Strength activity index, at 28 days, percent of control (%)	Min, 75	80

- Water absorption.

This experiment was carried out according to BS 1881-122 (2011). The diameter and thickness of each core were 75 and 100 mm, respectively. Tests of the electrical resistance of concrete, bulk electrical conductivity, and chloride migration coefficient were conducted at the age of 90 days. Cylindrical specimens were cured in a curing room until the intended age.

- Electrical resistance of concrete.

Although there is not any standard for this experiment, it is a useful and cost-effective method to evaluate the durability of concrete. We applied a stable voltage across two copper plates at the ends of the cylindrical specimens and measured the electrical resistance. A little mortar was used to hold the copper plates to the specimens:

$$\varphi = V/I \quad (1)$$

$$k = A/l \quad (2)$$

$$R = \varphi \times k, \quad (3)$$

where φ is the electrical resistance of concrete, K is the correction factor, A is the area that current pass (m^2), and L is the height of specimen that current pass (m).

- Bulk electrical conductivity.

In accordance with ASTM C1760 (2012) standard, a voltage of 60 V was applied to the ends of the cylindrical saturated specimens and the current was measured at 1 min. The diameter and height of specimens were 100 and 200 mm, respectively.

- Chloride migration coefficient (RCMT).

This experiment was carried out according to NT BUILD 492 (2011).

Results and Discussion

The results of experiments were as follows.

The Results of Copper Slag's Pozzolanic Specification

Based on Table 1, copper slag can be referred to as a pozzolan. Figure 1 shows that this type of copper slag is amorphous. The summation of silica, alumina, and iron oxide in the copper slag is 76%, slightly more than the emphasized limit of 70%, according to ASTM C618. Harmful oxides, too, are within the allowable range, according to ASTM C618.

Workability

Table 5 shows the results of workability. The slump relationship with the *w*/*b* ratio, copper slag, and cement factor is presented in Figs. 3, 4, and 5. Slump changed in the range of 20–110 mm. Workability of samples 4 and 8 was minimum and maximum, respectively. Considering the same *w*/*b* ratio and cement factor, workability difference between samples 6 and 8 was remarkable. Cement admixtures (copper slag and silica fume) were the only difference between the two samples. Silica fume was almost ineffective in workability (in this range of *w*/*b* ratio). Therefore, the copper slag was the effective factor and efficient in improving workability, especially in low *w*/*b* ratios.

Figures 3, 4, 5, and 6 show that an increase in cement factor, *w*/*b* ratio, and slag increases the amount of slump. These figures also show how copper slag and *w*/*b* ratio increase the slump. The effects of copper slag and *w*/*b* ratio are similar on changes of slump. Whereas free water is the most important factor in workability, each factor that increases it amount (such as cement factor, *w*/*b* ratio, and copper slag) increases slump. Copper slag is very effective in the slump; it reduces the water demand.

Table 5 Results of all experiments

Number of samples	Slump (mm)	28-day compressive strength (MP)	90-day compressive strength (MP)	Water absorption (%)	Electrical resistance (Ωm)	Bulk electrical conductivity (mS/m)	Migration coefficient ($\times 10^{-12}$ m^2/s)
1	90	42	45	2.1	54	12.97	8.5
2	75	41	42	1.8	458	4.82	2.06
3	70	45	52	2.25	249	3.41	2.56
4	110	36	40	2.37	99	9.77	9.92
5	80	45	53	1.7	108	8.31	5.14
6	75	41	52	1.6	376	2.31	0.35
7	80	49	50	1.85	215	6.37	3.8
8	20	54	56	1.7	113	7.97	10.48
9	95	31	38	2.4	115	9.8	7

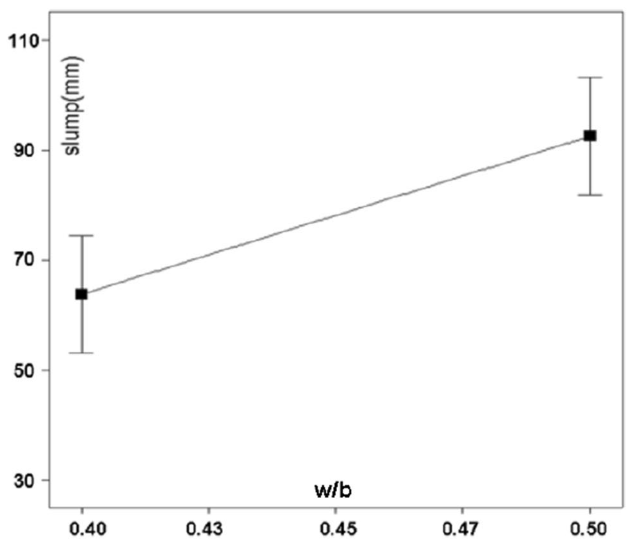

Fig. 3 Slump changes with respect to the *w/b* ratio

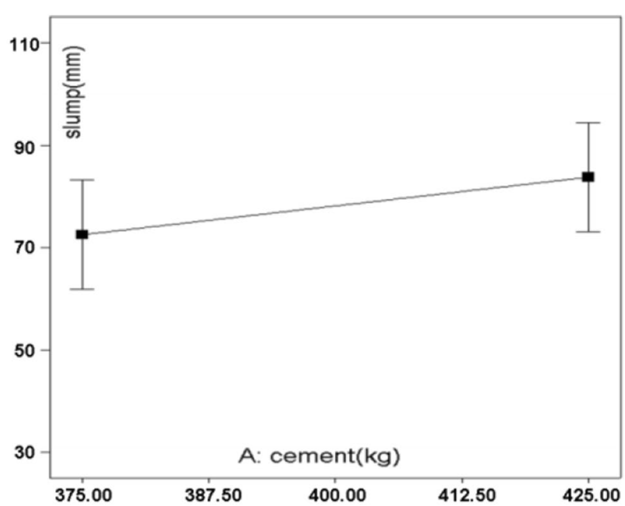

Fig. 4 Slump changes with respect to the cement factor

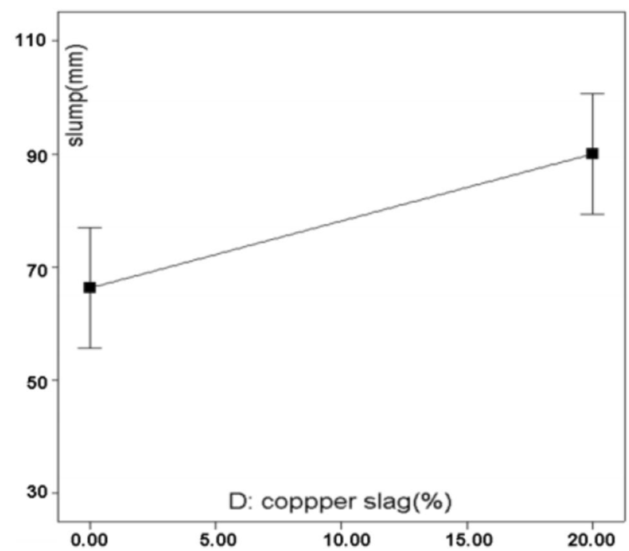

Fig. 5 Slump changes with respect to the copper slag

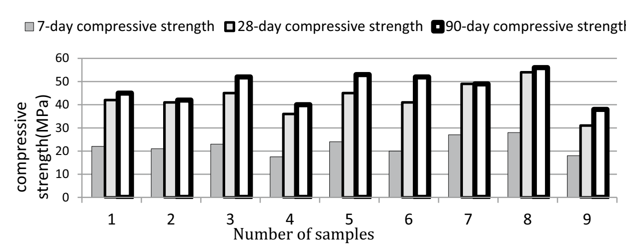

Fig. 6 Comparing the compressive strength of concrete used at ages 7, 9, 28, and 90 days

Compressive Strength

Table 5 shows the results of compressive strength. Figure 6 shows the comparison of the compressive strength at 7, 28,

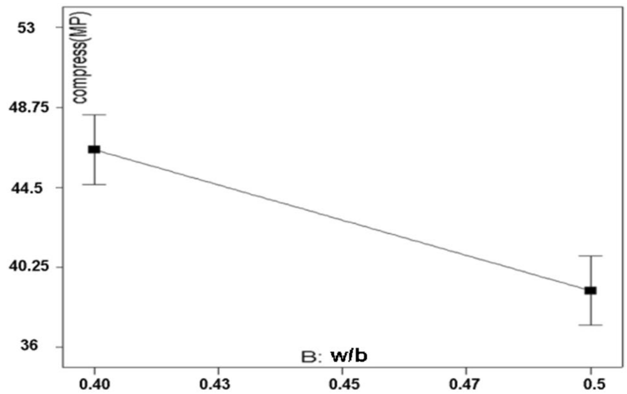

Fig. 7 Strength changes with respect to the *w/b* ratio

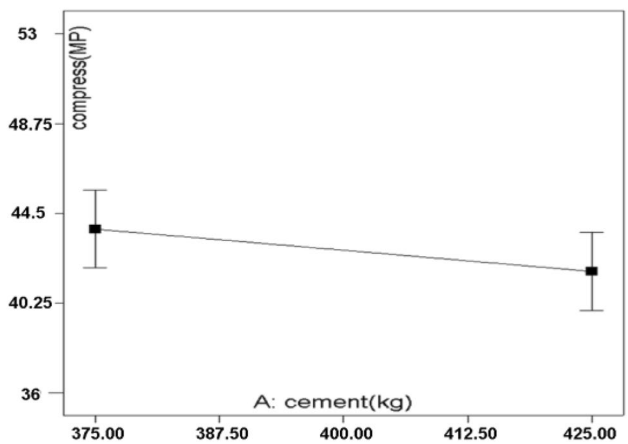

Fig. 8 Strength changes with respect to the cement factor

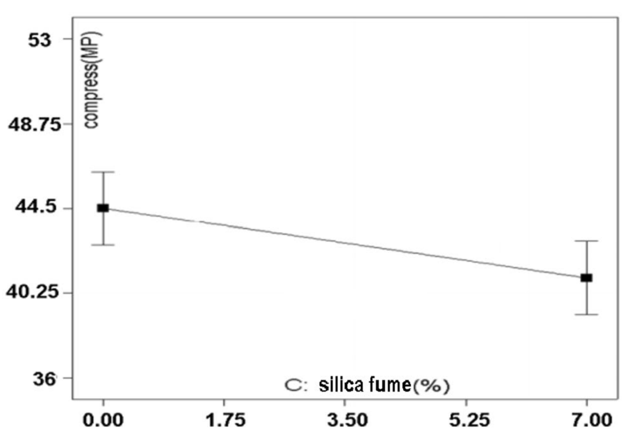

Fig. 9 Resistance changes with respect to the silica fume

and 90 days. Figures 7, 8, 9, and 10 show the strength relationship with the *w/b* ratio, copper slag, cement factor, and silica fume.

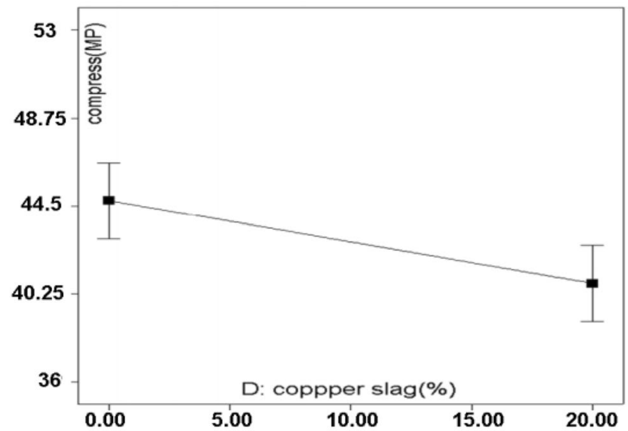

Fig. 10 Resistance changes with respect to the copper slag

Compressive strength of samples containing copper slag at an earlier age (28 days) was less than that of the control samples, but the differences decreased at a later age, especially in lower *w/b* ratios. Comparing sample 8 with samples 6 and 5 would prove this point. The compressive strength of samples with *w/b* ratio of 0.4 is higher than 50 Mpa at 90 days of age, which is suitable for durable concrete. The rate of hydration in the samples containing copper slag is less than that of the control sample.

Figures 7, 8, 9, and 10 show that compressive strength decreases when either *w/b* ratio or cement factor increases. One of the first steps of destruction, and strength and durability reduction is increased pores in the structure of mortar and ITZ phase. *w/b* ratio is one of the most effective factors in the amount of pores.

Raveendran et al. (2015) declared that silica fume increases compressive strength and the best percentage of replacement with cement in 10%. Edwin et al. (2016) found using copper slag as a partial replacement for cement up to 20% does not have any considerable negative effect on compressive strength. Al-Jabri et al. (2006) also found that as slag increased to more than 13.5%, and compressive strength was reduced.

Water Absorption

Table 5 shows the results of water absorption. Figures 11 and 12 show the relationship between water absorption on one hand and the *w/b* ratio and cement factor on the other hand. Water absorption decreases when the either *w/b* ratio or cement factor increases. The increase in mortar volume is the cause of increased water absorption. Copper slag and silica fume do not appear to affect water absorption. Geetha and Madhavan (2017) found the sorptivity ranged between 0.1 and 0.25 mm/min when copper slag and fly ash were

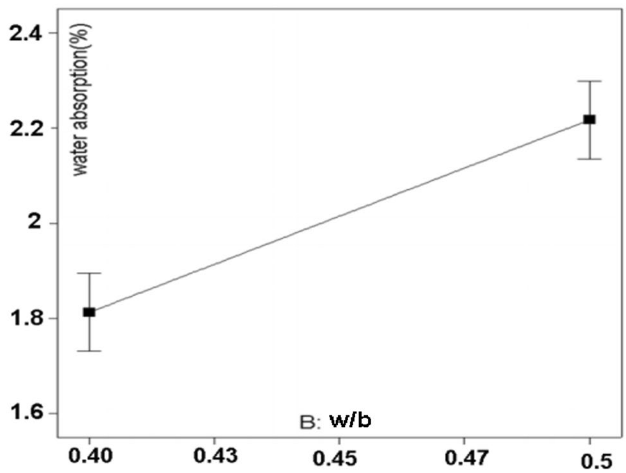

Fig. 11 Effect of *w/b* on water absorption

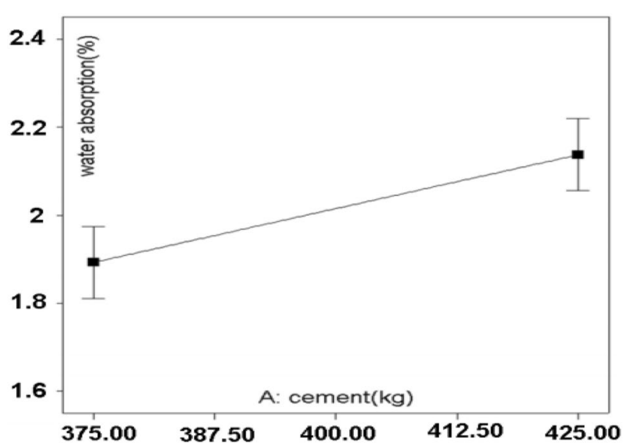

Fig. 12 Effect of cement factor on water absorption

used as a partial replacement for cement which shows little permeation to control sample.

Electrical Resistance of Concrete

Table 5 shows the results of electrical resistance. Figures 13, 14, 15, and 16 show the electrical resistance's relationship with the *w/b* ratio, copper slag, cement factor, and silica fume.

The higher value of electrical resistance presents a more durable mix design. The electrical resistance changes fall within the range of 54–376 Ω. Samples 6 and 1 have the maximum and minimum values, respectively. *w/b* ratio and cement factor of sample 6 are the minimum and the values of silica fume and copper slag are the maximum of the range. Samples 6 and 1 are in opposite positions with each other. This elucidates the effects of variables on electrical resistance of concrete values. The maximum values are samples

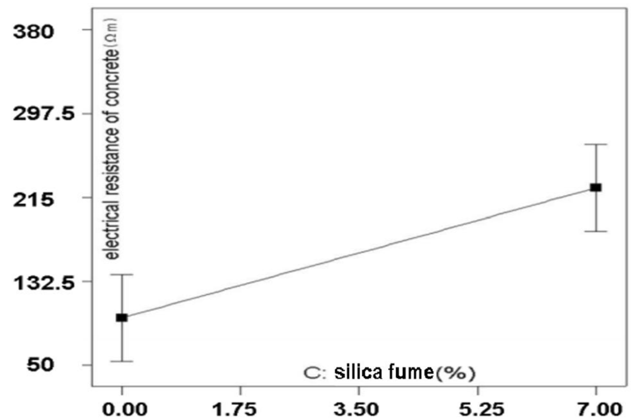

Fig. 13 Electrical resistance changes to silica fume

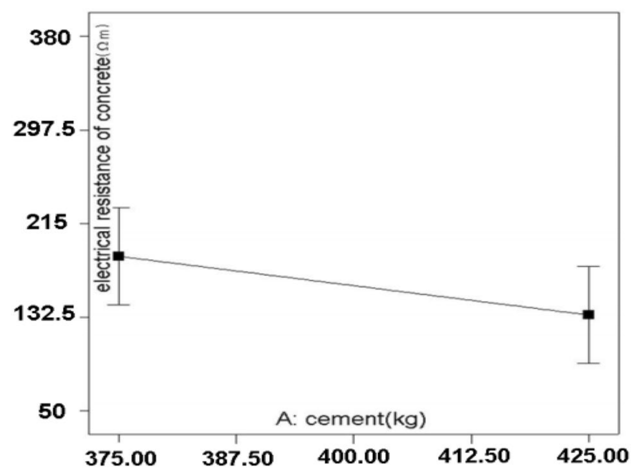

Fig. 14 Electrical resistance changes to cement factor

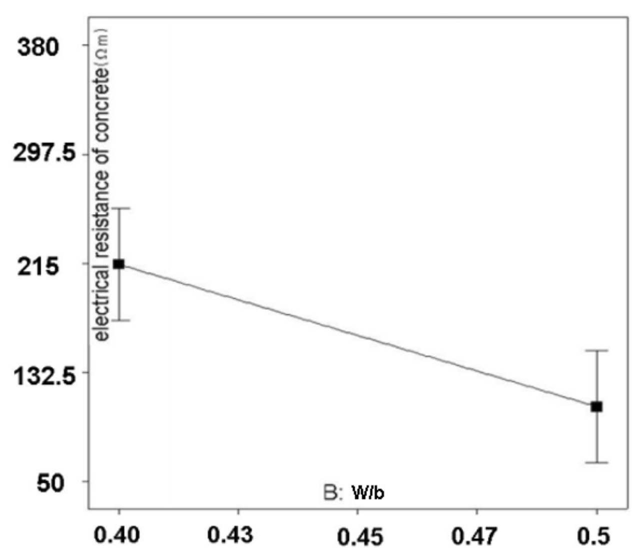

Fig. 15 Electrical resistance changes to *w/b*

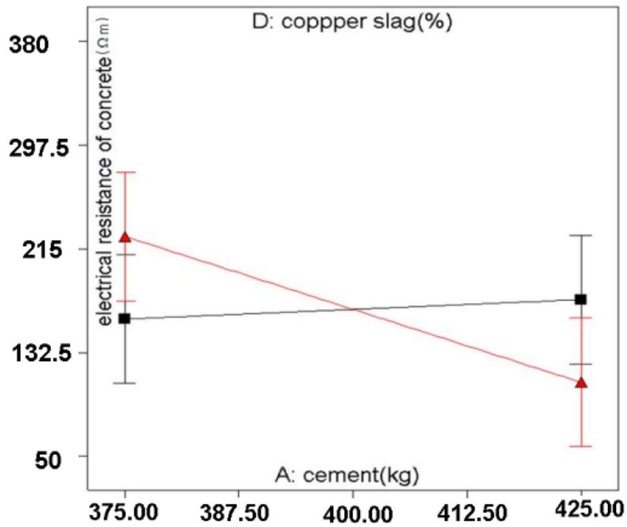

Fig. 16 Electrical resistance changes to cement factor and copper slag

2, 6, 3, and 7 which contain silica fume. Comparing sample 5 with samples 8, and sample 4–sample 1 indicates the positive effect of copper slag.

In Fig. 16, red and black line show how electrical resistance changes when cement factor increases in maximum and minimum values of copper slag, respectively.

According to Figs. 13, 14, 15, and 16, silica fume and *w*/*b* ratio are the most effective factors in electrical resistance. Increasing cement factor and *w*/*b* ratio decreases electrical resistance. A decrease in silica fume increases electrical resistance. However, copper slag does not appear to have any (significant) effect.

This experiment indicated the resistance of concrete against aggressive ions. Water-filled pores help conduct electrical current inside the samples. The amounts of pores and their properties can be considered important factors in providing ions the opportunity to diffuse in concrete; these can also indicate the rate of penetration (Gao et al. 2014). These studied variables are effective factors in pore and concrete properties. *w*/*b* ratio is one of the most effective factors in the size and continuity of capillary pores. According to Table 1, silica fume and copper slag are the lack of CaO and containing a significant amount of Silica (Trigo and Liborio 2014). The slag improves the formation process of C–S–H gel during hydration. Slag and silica fume assist the development of cement hydration, and increase the density of ITZ. Silica fume can fill pores and contribute to hydration, which can in turn increase the possibility of C–S–H gel formation. Due to containing a high percent of iron oxide, copper slag increases electrical conductivity. Therefore, this issue interferes with the results of durability experiments and reduces the positive effects of copper slag. However, the results of samples containing copper slag were better than those of control samples. It was found that the admixture of silica fume with other minerals as metakaolin can improve concrete durability (Yoo et al. 2010; Anbarasan and Venkatesan 2015).

Bulk Electrical Conductivity

The results of bulk electrical conductivity are summarized in Table 5. Figures 17, 18, and 19 show the bulk electrical conductivity relationship with the *w*/*b* ratio, cement factor, and silica fume. Due to having the lowest value, sample 6

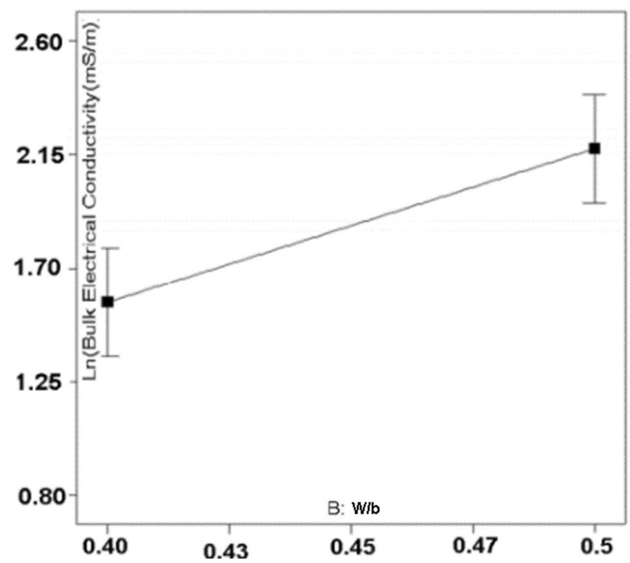

Fig. 17 Effect of *w*/*b* on electrical conductivity

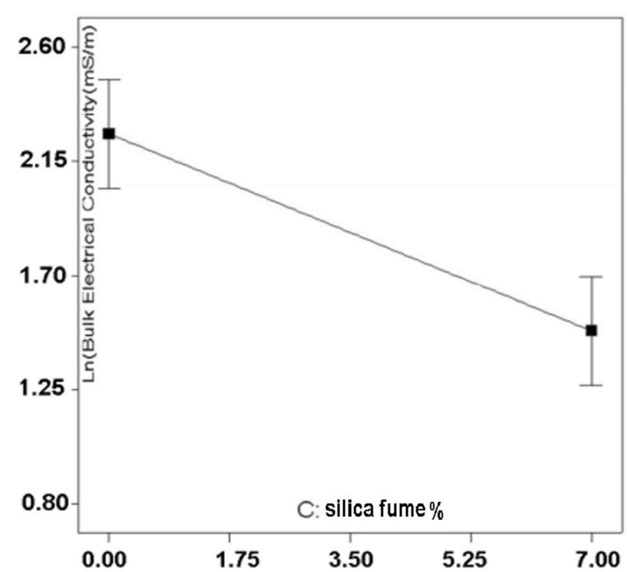

Fig. 18 Effect of silica fume on electrical conductivity

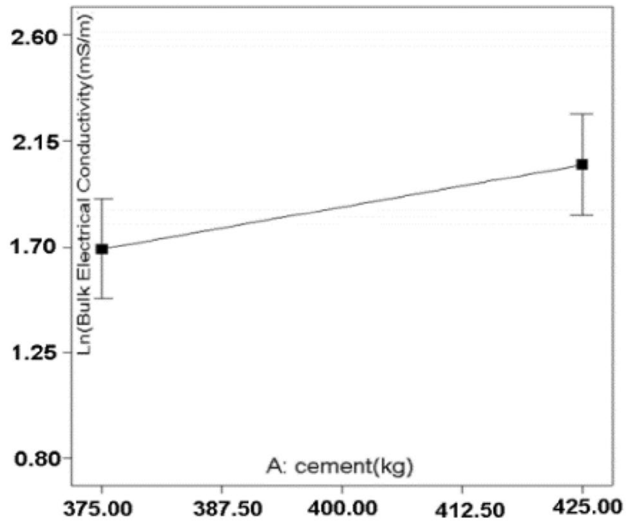

Fig. 19 Effect of cement on electrical conductivity

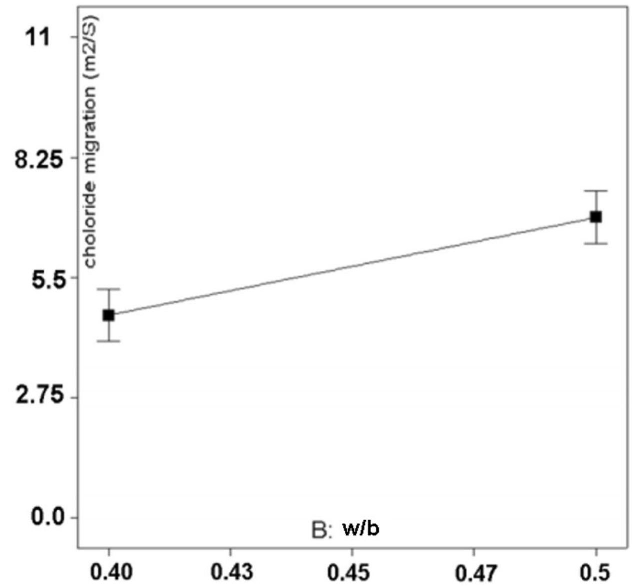

Fig. 20 Effect of *w*/*b* on RCMT

can yield the best results in sensitive areas such as coasts. According to experiments of bulk electrical conductivity and electrical resistance, samples which contain silica fume enjoy acceptable durability results. Although copper slag is not as effective as silica fume, comparing samples containing copper slag with control samples in both *w*/*b* ratio of 0.4 and 0.5 proves the positive effect of copper slag on durability. This issue becomes evident through the comparison of sample 5 with sample 8, and sample 4 with sample 1.

Figures 17, 18, and 19 indicate that the results are completely similar to those of electrical resistance. An increase in silica fume has a positive effect on the results of bulk electrical conductivity. However, increases in the *w*/*b* ratio and cement factor displayed a negative effect. Najimi et al. (2011) emphasized the effectiveness of copper slag replacement in improving the concrete resistance against sulfate attack which is a key factor in durability. Wang et al. (2017) also declared that using 25% fly ash and 5–8% silica fume as the replacement for cement led to significant improvements in the resistance of concrete against combined freezing–thawing and sulfate attack.

Chloride Migration Coefficient

The results of this test are presented in Table 5 at the age of 90 days. Figures 20, 21, and 22 show the chloride migration coefficient relationship with the *w*/*b* ratio, copper slag, and silica fume. Type of change and maximum and minimum points was the same in the three experiments of durability. Samples 6 and 1 had the minimum and maximum values, respectively. Samples 2, 6, 3, and 7, which contain silica fume, displayed minimal values. Comparing sample 5 with sample 8 and sample 4 with sample 1 indicates the positive effect of copper slag.

According to Figs. 20, 21, and 22, chloride migration coefficient results are closely similar to electrical resistance and bulk electrical conductivity. The increase in silica fume had a positive effect on the results of chloride migration coefficient, while an increase in the *w*/*b* ratio produced a negative effect. Copper slag has a slight, positive effect.

Yoo et al. (2010) found silica fume as an effective factor in decreasing chloride migration coefficient. Pilvar et al. (2018) also found that applying SF reduces the chloride

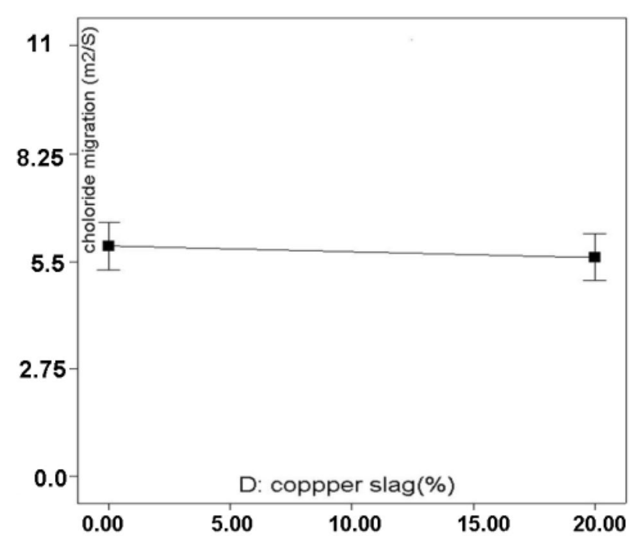

Fig. 21 Effect of slag on RCMT

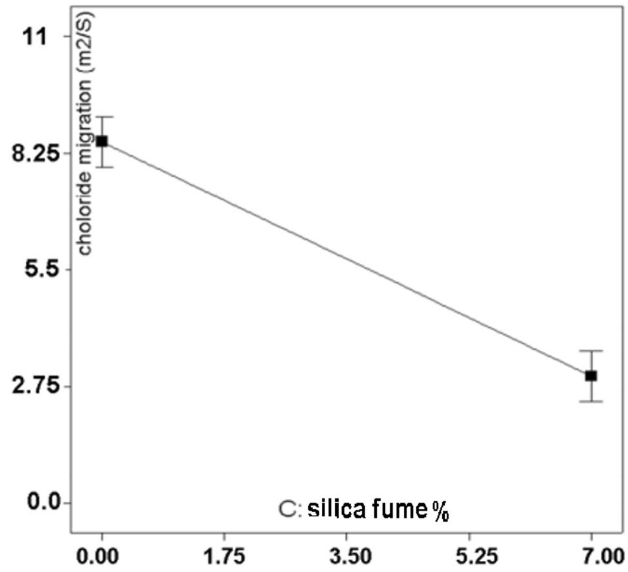

Fig. 22 Effect of silica fume on RCMT

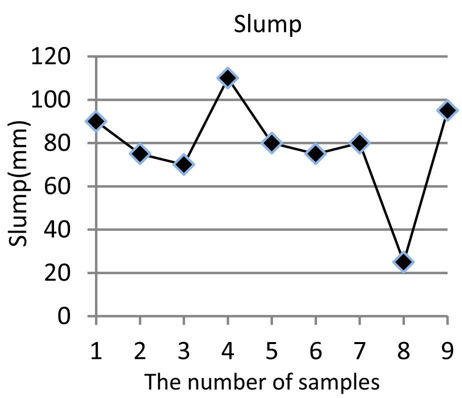

Fig. 23 Slump changes

permeability of concrete. Geetha and Madhavan (2017) found that there was an appreciable decrease in the chloride ion penetrability (Coulombs), as the fly ash content, silica fume, and copper slag were used as cement replacement. They found optimized values of silica fume, copper slag, and fly ash at 10%, 20%, and 17%, respectively.

As copper slag improves slump in stable mortar volume, it can decrease chloride migration coefficient via decreasing the volume of mortar and *w*/*b* which is the most important factor in durability.

Comparing Experiments Results

The summarized results of the experiments are presented in Figs. 23, 24, 25, 26, 27, and 28 which show the style of

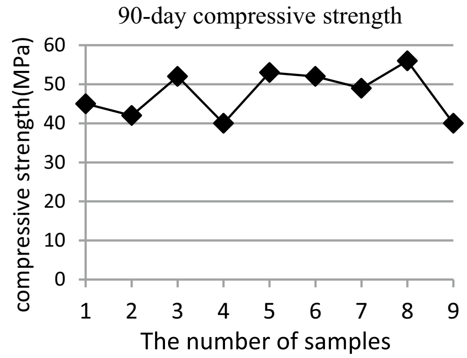

Fig. 24 Compressive strength changes

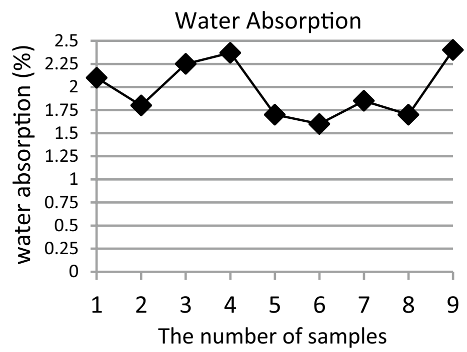

Fig. 25 Water absorption changes

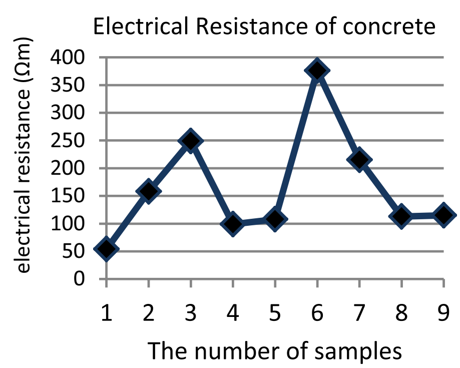

Fig. 26 Electrical resistance changes

changes in charts. As can be seen in Figs. 26, 27, and 28, the change patterns of triple durability experiments (containing electrical resistance of concrete, bulk electrical conductivity, and chloride migration coefficient) are remarkably similar. Compressive strength and water absorption match identically. In sample 8, the loss of pozzolan created a discrepancy between compressive strength and triple durability experiments.

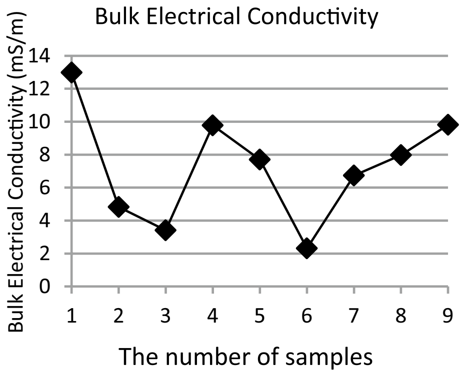

Fig. 27 Electrical conductivity changes

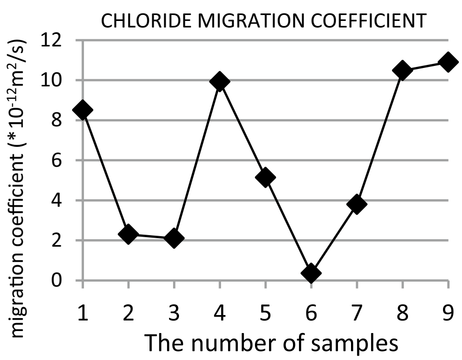

Fig. 28 Chloride migration coefficient changes

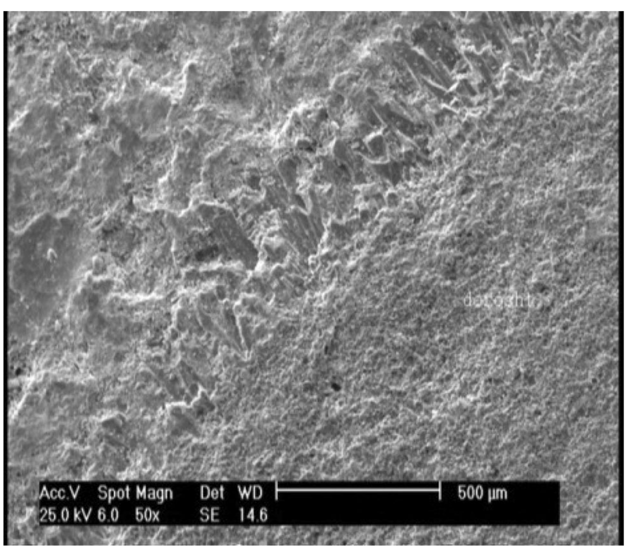

Fig. 29 Zoom up to 50 times

SEM and XRD

Figures 31, 32, 33, 34, 35, 36, 37, and 38 show SEM of four samples 3, 5, 6, and 8 which cured at 90 days. *w*/*b* ratio of these samples was constant, 0.4, but other factors were variable. Electron image indicated the ITZ microstructure. Figures 29 and 30 show the space between coarse aggregate and bulk paste. The SEM of aggregate is presented in Fig. 39 depicting the specific microstructure discrepancy between the mortar and aggregate. ITZ thickness was up to 100 µm (Fig. 29) and it was impossible to clarify a clear boundary between the ITZ and bulk paste. In SEM images, difference of sample 8 is evident (Figs. 35, 36, 37, 38); it is more portlandite than other samples, which is proven by XRD. CH phase is defined in Fig. 36.

The ITZ porosity depends on casting factors, curing age, *w*/*b* ratio, and aggregate content (Gao et al. 2014). Although

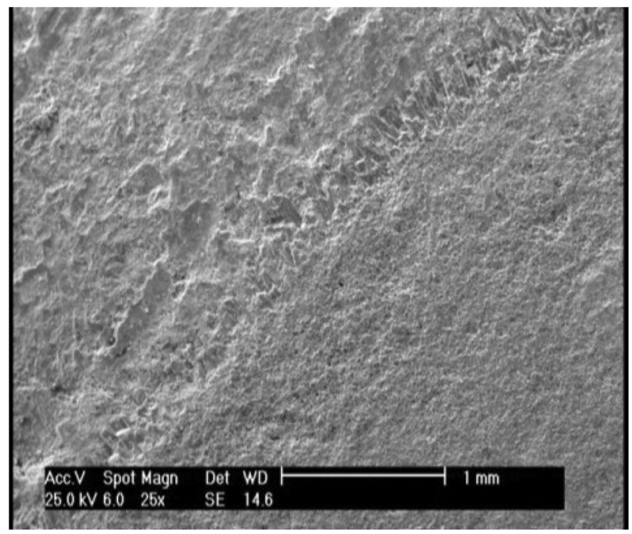

Fig. 30 Zoom up to 25 times

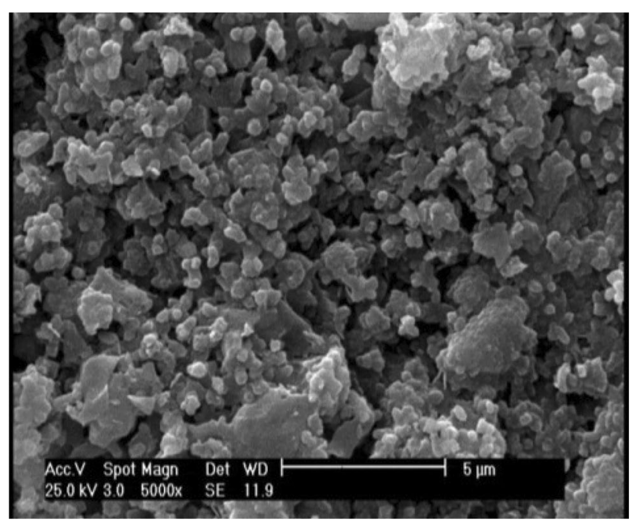

Fig. 31 SEM of sample 3, zoom up to 4000 times

aggregate penetration is negligible in comparison with other phases, it is effective in the values of other phases, especially ITZ. Since ITZ is more permeable than cement phase, the pore network increases in concrete microstructure. It reduces durability in high *w*/*b* ratio, but has the converse effect in lower ratios especially when containing a suitable pozzolan such as silica fume.

ITZ is not fully understood and is more permeable than cement phase (Gao et al. 2014; Liu et al. 2014). Higher porosity and different texture compared to cement can account for this issue. Silica fume increases density of ITZ because of reduced porosity (Gao et al. 2014).

The results of sample 6 are desirable in all experiments on fields of workability, strength, and durability. It introduces mix design of sample 6 as an optimal one. The simultaneous existence of copper slag and silica fume as a partial replacement for cement decreases the possibility of CH formation. Low *w*/*b* ratio and suitable cement admixture reduce capillary pores in ITZ and cement phase as well.

It can be claimed, by the expression of durability experiments such as electrical resistance of concrete, bulk electrical conductivity, and chloride migration coefficient, that there are two types of conductivity, the first being caused by filling pores with water, and the other occurring due to conductivity of concrete materials. Certainly, the aim of

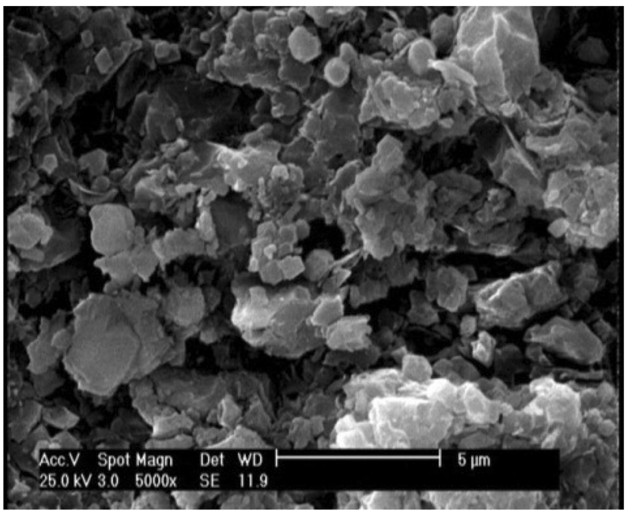

Fig. 32 SEM of sample 3, zoom up to 4000 times

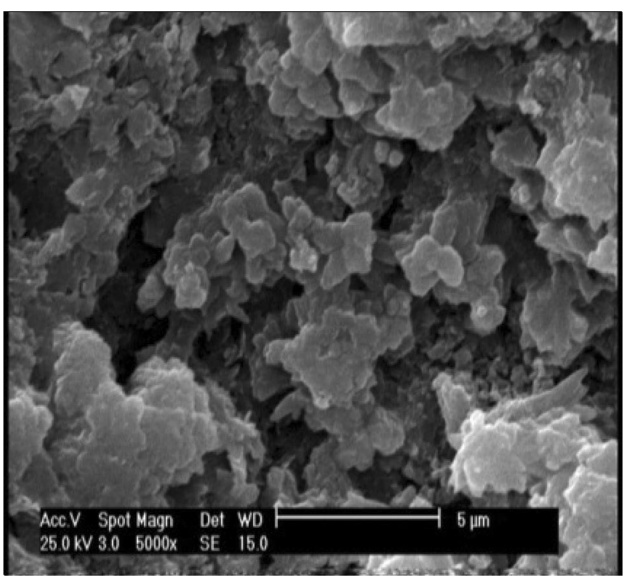

Fig. 33 SEM of sample 5, zoom up to 4000 times

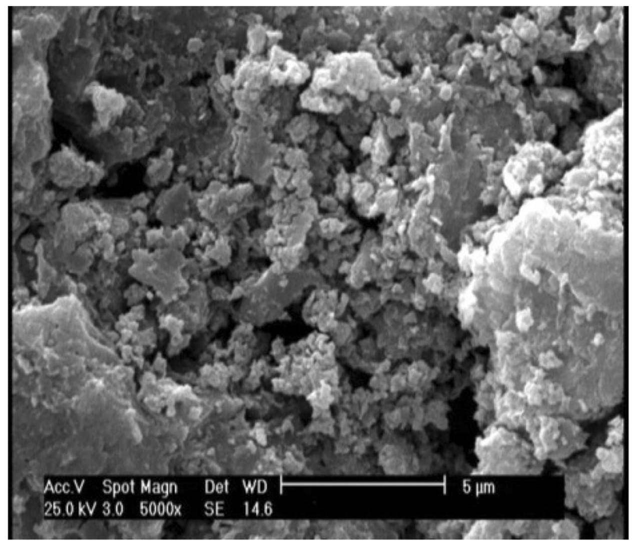

Fig. 34 SEM of sample 6, zoom up to 4000 times

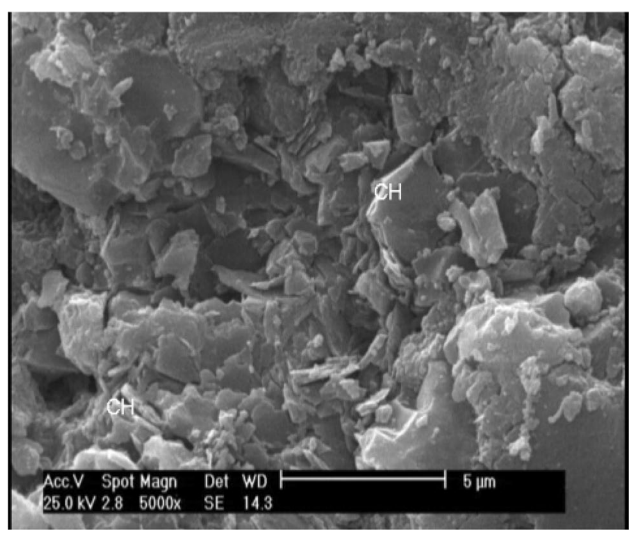

Fig. 35 SEM of sample 8, zoom up to 4000 times

durability experiments was conductivity measurement of the first type.

Figures 40 and 41 show XRD analysis of samples 6 and 8.

Economic Issues

Economic justification is presented in Fig. 42. Examples 3 and 4, respectively, present the highest and the lowest cost and sample 6 shows almost an average cost. Sample 6 is preferable from an economic standpoint. Furthermore, strength and durability are appropriate.

Conclusion

This study considered the effects of four variables including cement factor, *w*/*b* ratio, copper slag, and silica fume on the fields of workability, strength, durability, and economic issues. Sample 6 proved to be the best response with these specifications of cement factor of 375, *w*/*b* ratio of 0.4, and 7% and 20% of cement replaced with silica fume and copper slag, respectively. Suitable percentages of copper slag and silica fume in concrete can conclude desired results on workability, strength, and durability if the values of cement factor and *w*/*b* ratio are chosen appropriately.

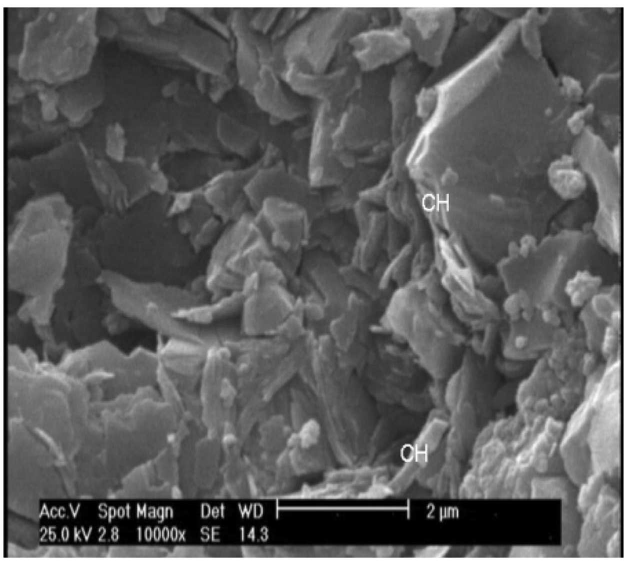

Fig. 36 SEM of sample 8, zoom up to 4000 times

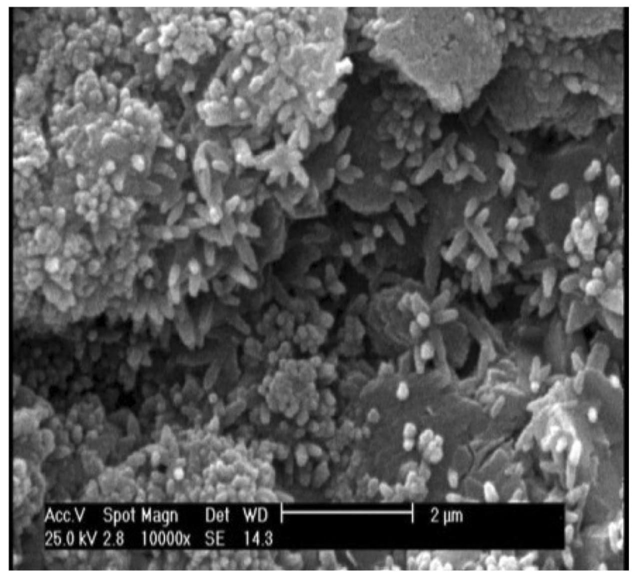

Fig. 38 SEM of sample 8, zoom up to 4000 times

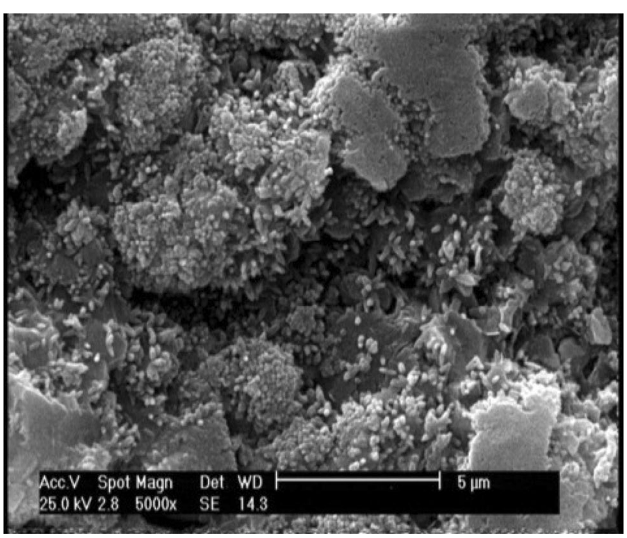

Fig. 37 SEM of sample 8, zoom up to 4000 times

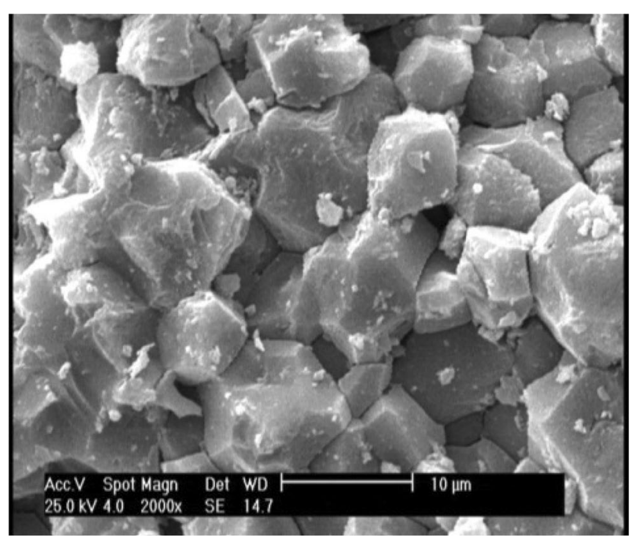

Fig. 39 SEM of aggregate, zoom up to 4000 times

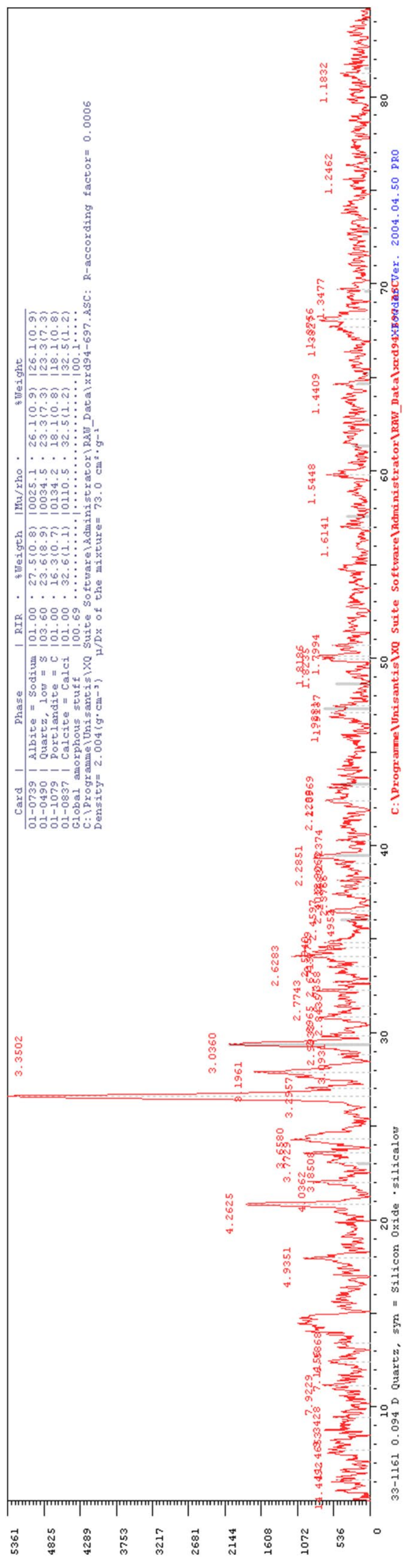

Fig. 40 XRD of sample 6

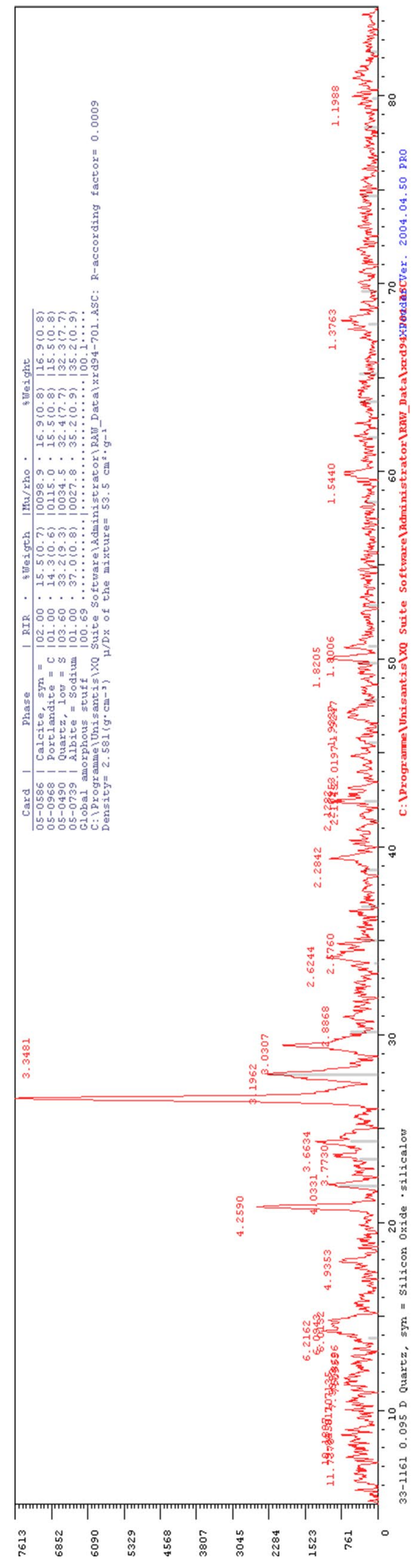

Fig. 41 XRD of sample 8

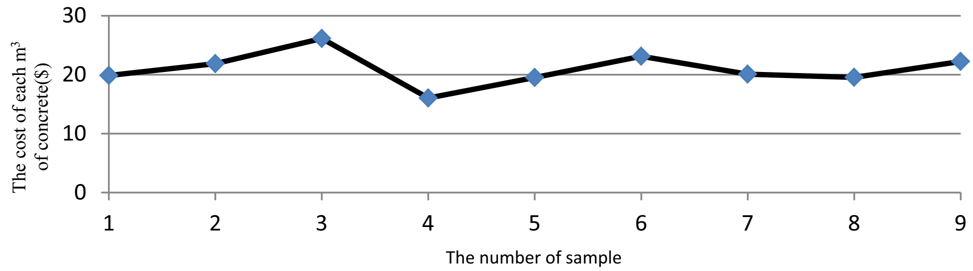

Fig. 42 Economic estimation of mix designs

The best effect of copper slag was on the field of workability. Copper slag improved workability desirably; meanwhile, it did not decrease the values of strength and durability. The results of durability and strength of samples containing slag were more acceptable than those of the control samples.

All these four variables were optimized in sample 6 and all fields of workability, strength, durability, and economic issues displayed the best values. Concrete microstructure improved via optimization of effective factors and use of suitable concrete admixture. When two factors of *w*/*b* ratio and cement factor were the same, different results of compressive strength and durability tests (containing electrical resistance of concrete, bulk electrical conductivity, and chloride migration coefficient) indicate that durability results depend largely on the concrete admixtures, such as silica fume (apart from optimizing factors as *w*/*b* ratio and cement factor), which improve concrete microstructure.

When cement factor and *w*/*b* ratio were minimum, positive effect of copper slag was more evident on fields of workability, durability, and strength, especially at a longer curing age. When the curing age increased from 28 to 90 days, resistance differences between control samples and experimental samples containing copper slag were reduced.

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