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Concrete Behaviour with Volcanic Tuff Inclusion

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Abstract This study evaluates the effect of substituting cement by volcanic tuff on the workability, mechanical properties, and durability of concrete. Five mixtures were prepared with volcanic tuff ratios to cement of 0%, 5%, 10%, 15% and 20%. First, X-Ray Fluorescence (XRF) test for volcanic tuff was performed. Then, slump test was conducted for fresh concrete specimens. Moreover, tests for flexural strength, splitting tensile strength, elevated heat resistance, ultrasonic pulse velocity, and Scanning Electron Microscope (SEM) were performed at 28-days age of concrete specimens. Compressive strength, and absorption tests were conducted at 28, and 56-days ages of specimens. The study showed that slump, compressive strength, flexural strength, and splitting tensile strength were decreased with the increasing of volcanic tuff to cement replacement ratio at 28-days age. Additionally, the highest compressive strength and lowest water absorption for concrete were obtained at 56-days age of specimens and 10% volcanic tuff to cement replacement ratio.

Keywords Volcanic Tuff, Compressive Strength, Natural Pozzolan, Concrete, Cementitious Material

1. Introduction

Currently, the use of cement in concrete has negative environmental impacts due to the large number of carbon dioxide emissions during its manufacturing process. Meanwhile, cement is considered the most expensive ingredient in concrete because it consumes a large amount of energy during production which affecting the economic aspect of the concrete industry. Accordingly, it was necessary to search for materials that can be used as a supplementary of cement. These supplementary cementitious materials should be available, inexpensive, and can improve the properties of concrete. Different substitution materials will have different effects on the properties of the cement due to their chemical, physical and mineralogical characteristics [1–3].

Pozzolanic materials are widely used as supplementary cementitious materials in concrete. Pozzolanic materials can be classified to natural and artificial pozzolanic materials. Natural pozzolanic materials are materials such as zeolite, and volcanic tuff, while artificial pozzolanic materials are materials such as silica fume, fly ash, and metakaolin [4–6]. Volcanic tuff is one of the most pozzolanic materials which can be found as a natural material in Middle East countries (such as Egypt, Jordan, and Saudi Arabia). Jordan has available huge quantities of volcanic tuff (estimated as 800 million tons) [7]. Consequently, volcanic tuff was chosen to be used as a supplementary cementitious material in this research.

The replacement of cement by pozzolanic materials could improve the mechanical properties of cement and concrete composites. Replacement dosages between 5 to 50% by weight of cement were commonly used [8–10].

The popular ratio of cement replacing with the natural pozzolans was 15 to 20 % [2]. Experimental research was studied on 0, 10, 30, and 50% of Portland cement weight replacement by analcime, and clinoptilolite contents. The authors demonstrated that the highest strengths were obtained from samples containing 10% of both analcime and clinoptilolite blended cement contents [11]. Metakaolin has been used as a partial substitution for cement in the range of 4% to 28% by weight of cement. The highest compressive strength achieved at 16% metakaolin to cement substitution ratio [12]. Previous studies showed that volcanic tuff which contains a large proportion of SiO_2 and Al_2O_3 improved the structural composition of cement mortar and concrete by forming additional C-S-H compound [10,13-15]. Other research illustrated that formation of C-S-H in hardened cement pastes enhanced the development of strength [8,16 −19].

In this research, volcanic tuff (natural Pozzolans) was investigated as a partial alternative material for cement in concrete. First, volcanic tuff was collected from mines located in the north of Jordan. Then, tests were carried out on concrete containing cementitious materials of volcanic tuff with 0, 5, 10, 15, and 20% cement replacement ratios. Fresh and hardened concrete properties were examined. The paper proceeds as follows, the experiments for concrete are illustrated. Then, results and discussion in addition to the conclusion are introduced at the end of paper.

2. Materials and Methods

2.1. Materials

Cement used in this study was Portland Pozzolan cement; Type II / P-P 42.5 N (JS 30–102007). The specific gravity was 3.15 g/cm^3, and the specific surface area was 4000 cm^2/g. Volcanic tuff used in the research was collected from mines located in north of Jordan. Chemical compositions of cement and volcanic tuff are presented in Table 1.

Table 1. Chemical Composition of Cement and Volcanic Tuff

Oxides (%)	CEM II/P-P 42.5 N	Volcanic tuff
SiO_2	19.07	34.39
Al_2O_3	2.39	4.59
Fe_2O_3	9.52	31.46
Cao	63.24	24.11
MgO	-----	0.49
Na_2O	0.014	-----
K_2O	0.18	1.3
SO_3	2.47	-----

Chemical compositions of volcanic tuff showed that total content of SiO_2, Al_2O_3, and Fe_2O_3 was found to be approximately 71%. This ratio is little more than the minimum requirement (70%) specified in ASTM C-618 for natural pozzolans. Volcanic tuff was grinded in Los Angeles machine then sieved through a sieve #200. The maximum particle size of volcanic tuff, used in this paper, was less than 75 μm.

Fine and coarse aggregates used for casting concrete mixtures were obtained from Irbid area, Jordan. Physical properties of sand and conventional crushed limestone aggregate used are shown in Table 2. Fig. 1 shows the relation between sieve opening size and passing percentage of fine and coarse aggregates.

Table 2. Physical Properties of Fine and Coarse Aggregates

Aggregate type	Fine Aggregate.	Coarse Aggregate.
D $_{max}$ (mm)	-----	25
Specific Gravity (Dry)	2.28	2.34
Specific Gravity (SSD)	2.41	2.44
Bulk Density (Kg/m^3)	-----	1521.8
Absorption (%)	5.59	4.09
Fineness Modulus	2.9	-----
Moisture Content (%)	3.73	2.02

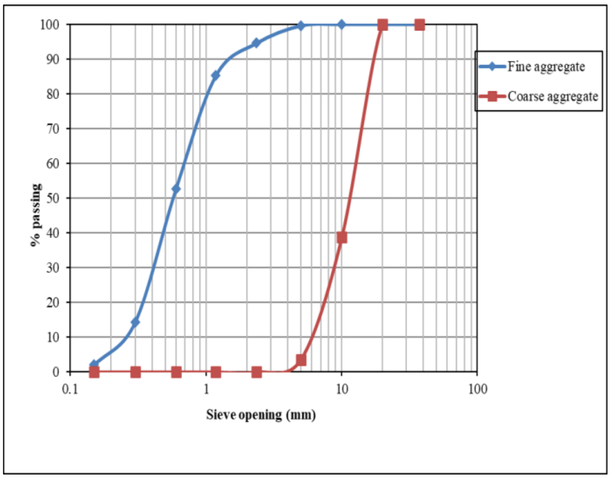


Figure 1. Relation Between Sieve Opening Size and Passing Percentage of Aggregate.

2.2. Methods

Five concrete mixtures, with 0, 5, 10, 15 and 20% of volcanic tuff cement replacement included, were used. All concrete mixtures were designed according to ACI C-211. A slump test of fresh concrete prepared with different percentages of volcanic tuff was performed according to ASTM C143.

A compressive test was performed to evaluate the strength development of 100 x 100 x 100 mm cubic specimens according to BS EN 12390-3:2009. Nine Cubic specimens were tested at 7, 28, and 56-days ages of curing (three cubes for each age) and the average compressive strengths were recorded. Compressive strength tests of all specimens were evaluated using a universal hydraulic testing machine (2000 KN capacity).

Four-point load flexural strength was tested for 150 x 150 x 750 mm concrete prisms according to ASTM C78 at 28 days age. A splitting tensile test was performed, according to ASTM C496, by universal hydraulic testing machine (2000 KN capacity). Six cylindrical specimens of 100 × 200 mm were tested at 7 and 28- days ages (three cylinders for each age). Tensile strength was calculated by dividing the maximum load (2P) sustained with geometrical factors (πDL).

Water absorption was tested for concrete specimens per ASTM C-642. Three specimens were cut into slices with a maximum thickness of 50 mm and 100 mm diameter for each concrete mix and tested for 28, and 56-days ages. Water absorption values were obtained by drying the specimens until a constant mass was achieved, immersed them in water, and measured the increase in mass as a percentage of dry mass.

Elevated heat resistance test was performed according to [20]. Three cubic specimens, at 28 days age of curing, were placed in an electrical furnace and heated at a fixed heating rate of 10 ℃/min to reach the elevated temperature of 250 ℃ and then compression tests were performed. The electrically heated furnace used here was designed for a maximum temperature of 3000 ℃.

An ultrasonic pulse velocity test was conducted on six cubic specimens at 28 and 56- days ages (three cubes for each age). The test equipment generates an amplified pulse and then transfers it through the concrete specimens. The transmission time for pulse that is taken through the concrete specimens was measured in microsecond (μs).

The microstructure study was undertaken to observe the structure of volcanic tuff concrete, including the effect of different mix formulations on the microstructure, presence of pores, and micro-cracks. Scanning Electron Microscopy (SEM) was performed on crushed concrete samples tested at 28 days age. SEM imaging was conducted on an EMITECH K550X. Concrete specimens were prepared using the mix design presented in Table 3.

Table 3. Mix Proportions of Concrete Control Mix

Designation	V0	V5	V10	V15	V20
Cement (gm)	320	304	288	272	256
Fine aggregate (gm)	626.5				
Coarse aggregate (gm)	1044				
W/Cm ratio	0.61				
Replacement ratio (%)	0	5	10	15	20
Volcanic tuff (gm)	0	16	32	48	64

3. Results and Discussion

3.1. Workability

For fresh concrete, a slump test was conducted for all mixes to study the effect of volcanic tuff as a cement replacement on the consistency of fresh concrete. Table 4 depicts that increasing replacement ratio of volcanic tuff decreased concrete workability by 8.3, 41.7, 66.7, and 66.7% for 5, 10, 15, and 20% replacement ratios, respectively. The cause, according to [21, 22], is that natural pozzolans (volcanic tuff) absorbs a high amount of mixture water due to their porous structure.

Table 4. Slump of Concrete Specimens Containing Volcanic Tuff

Percentage of volcanic tuff (%)	0	5	10	15	20
slump (mm)	120	110	70	40	40

3.2. Compressive Strength

Figure 2 shows the results for compressive strength of control mix and mixes with different replacement ratios of volcanic tuff at 7, 28, and 56-days ages. Fig. 2 demonstrates that at early ages (7 and 28 days), the control mix has the highest compressive strength among different concrete mixes.

At 7 days age, compressive strength decreased by 11.26, 20, 45.8, and 53.6% for 5, 10, 15, and 20% replacement ratios, respectively. Whereas, at 28 days age of specimen, compressive strength decreased by 4.1, 9.4, 38.22, and 47.8 for 5, 10, 15, and 20% replacement ratios, respectively.

At 56 days age, compressive strength increased by 21.5, and 25.7% for 5, and 10% replacement ratios and decreased by 20.4, and 28.9 for 15, and 20% replacement ratios, respectively.

This mainly is due to the decreasing of cement amount in blended cement mixture and, consequently, decreasing the amount of calcium silicate hydrates, C-S-H, which is responsible for strength development at 7-, and 28-days age [23]. While, at later age (56 days), low replacement levels (5 and 10 wt.%) of volcanic tuffs produced satisfactory compressive strengths. The increasing in compressive strength at later age (56 days), was observed when replacing cement by 10% of volcanic tuff due to the presence of a proportion of silicon oxide SiO_2, which in turn interacts with the un-hydrated calcium hydroxide $Ca(OH)_2$ and creates an additional bond of (C-S-H). This reaction occurs slowly, so the compressive strength increases over time as shown in Fig. 2.

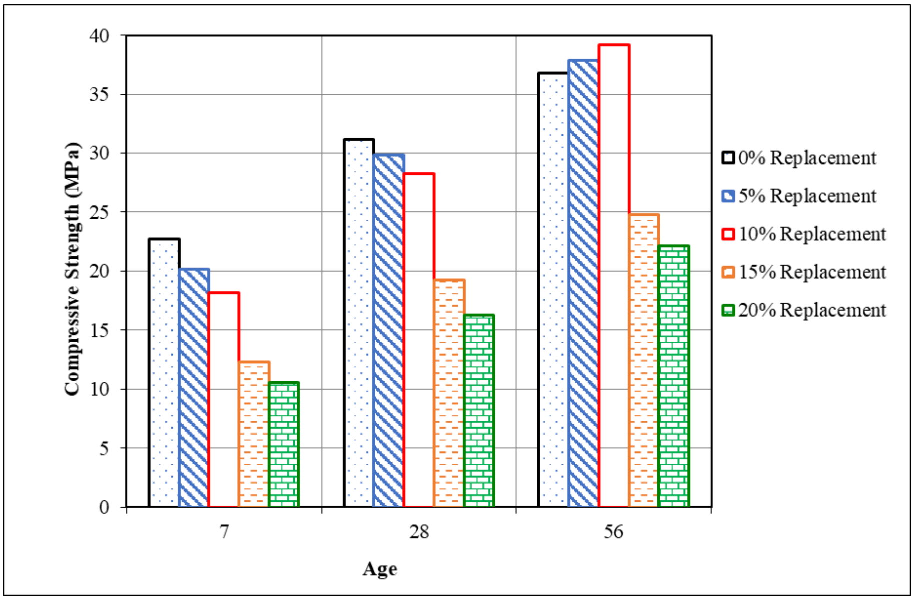


Figure 2. Compressive Strength of Concrete Cubes with Different Volcanic Tuff Ratios at 7, 28, and 56-Days Ages

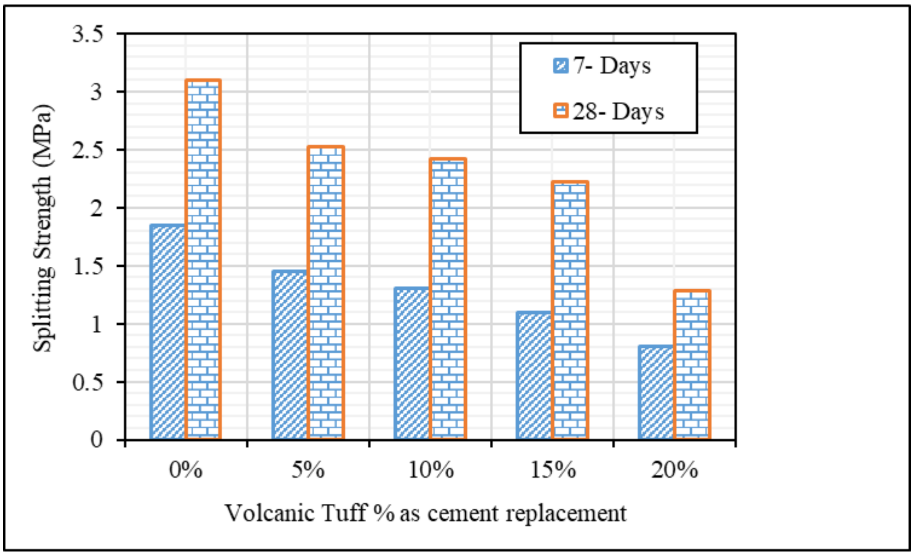


Figure 3. Splitting Tensile Strength of Concrete Cubes with Different Volcanic Tuff Ratios at 7, and 28-Days Ages

3.3. Splitting and Flexural Strengths

Splitting and flexural strengths of concrete for all partial replacement of cement by Volcanic Tuff at 7, and 28- days ages are plotted in Fig.3 and Fig. 4. respectively. It can be seen from Fig. 3. that, with increasing of volcanic tuff by 5, 10, 15, and 20% replacement ratios, the splitting tensile strength decreased by 21.6, 29.2, 40.5, and 56.8% at 7 days age, respectively. At 28 days age, the splitting tensile strength decreased by 18.4, 21.9, 28.4, and 58.7% for 5, 10, 15, and 20% replacement ratios, respectively.

The effect of volcanic tuff with different replacement ratios on flexural strength at 28 days age is presented in Fig. 4. Replacement of cement by volcanic tuff has slightly reduced the flexural strength by 8.7, 18.7, 28.4, and 58.7% for 5, 10, 15, and 20% replacement ratios, respectively. This can be explained by the increasing of Volcanic Tuff amount that leads to reduce the cement amount and significant retard of hydration which consequently decrease the amount of C_3S and C_2S.

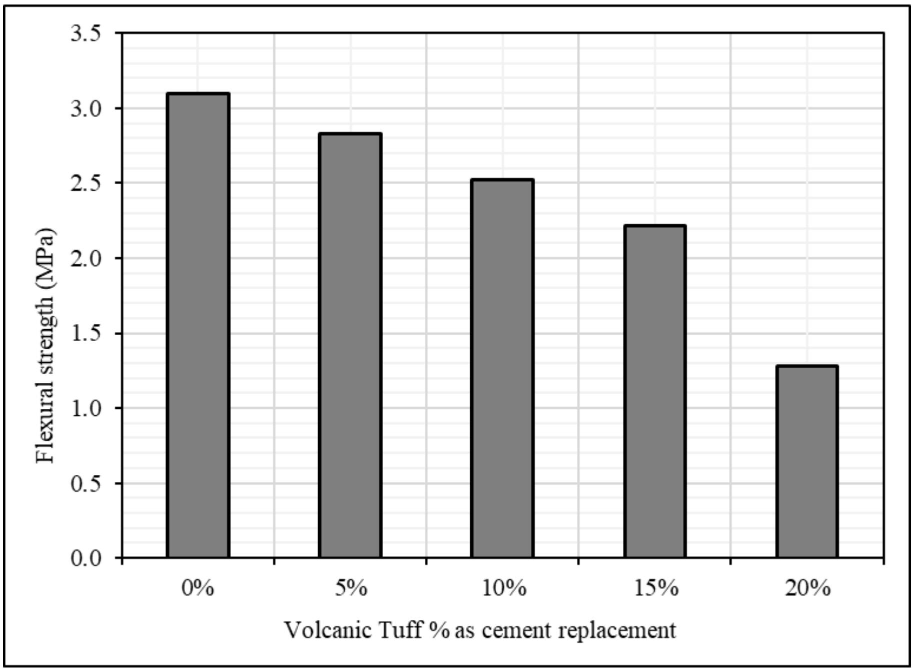


Figure 4. Flexural Strength of Concrete Prisms with Different Volcanic Tuff Ratios at the Age of 28 Days

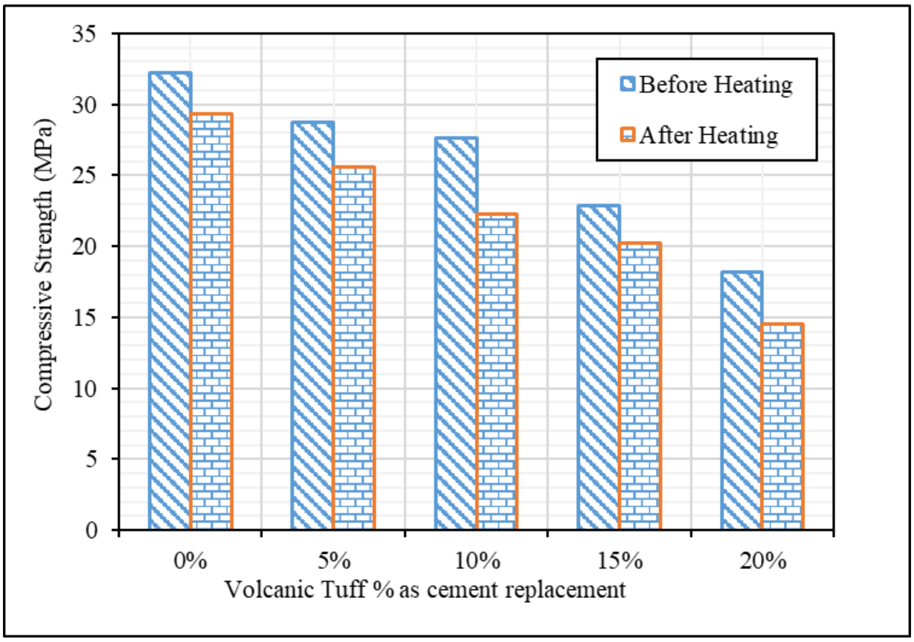


Figure 5. Compressive Strengths of Concrete Cubes with Different Volcanic Tuff Concentrations Before and After 250 ℃ Heated Temperature at 28 Days Age.

3.4. Elevated Heat Resistance

Fig. 5. shows the effect of elevated temperature on the compressive strength of concrete specimens with different levels of volcanic tuff. At 28 days age, compressive strength of control and partial cement replacement mixes with 5%, 10%, 15% and 20% were decreased after heating. This result is mainly due to an elevated temperature, the deterioration of calcium hydroxide, dehydration of calcium silicate hydrates, and thermal expansion mismatch of aggregates and hydrated cement paste [24].

3.5. Water Absorption

Table 5 shows concrete specimen's percentages of water absorption determined at 28, and 56- days ages. It can be noted that the replacement of cement by volcanic tuff has a slightly increasing effect on water absorption at 28 days age by 11.1, 11.6, 16.8, and 19.9% for 5, 10, 15, and 20% replacement ratios, respectively. At 56 days age, water absorption decreased by 1.9, and 5% for 5, and 10% replacement ratios and increased by 3.6, and 11.3% for 15, and 20% replacement ratios, respectively. These results can be attributed to voids increasing which cause reduction in durability.

Table 5. Percentage of Concrete Absorption at 28, and 56- Days Ages

Volcanic Tuff (%)	28-Days	56-Days
	Absorption (%)	
0	6.38	5.82
5	7.09	5.71
10	7.12	5.53
15	7.45	6.03
20	7.65	6.48

3.6. Ultrasonic Pulse Velocity

Fig. 6. shows values of time (µs) determined for 28, and 56- days ages versus volcanic tuff percentage as cement replacement. At 28 days, the time that a pulse should cross the 100 x 100 x 100 mm cube increased by 1.1, 1.4, 2.4, and 2.9% for 5, 10, 15, and 20% replacement ratios, respectively. Whereas, at 56 days age, pulse time decreased by 0.44, and 0.88 for 5, and 10% replacement ratios then increased by 1.3, and 1.8 for 15, and 20% replacement ratios, respectively.

The time that pulse takes through cube is an indication of the length that it took where it flows in the hardened concrete. So, as the time increase the voids increase. The trends shown in both absorption and ultrasonic pulse velocity can be explained by the low-rate pozzolanic reactions that produce C-S-H, yielding a decrease in porosity and increase of strength [25].

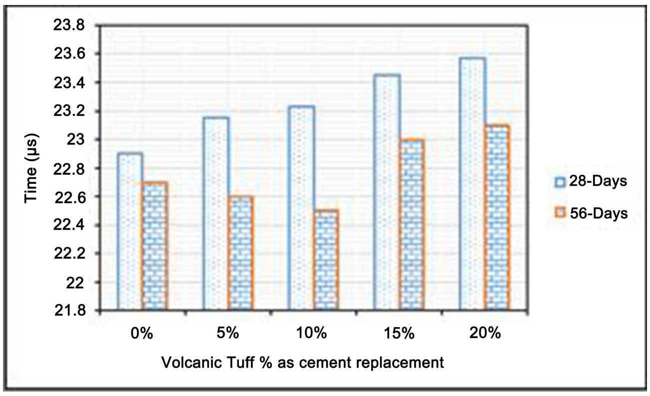


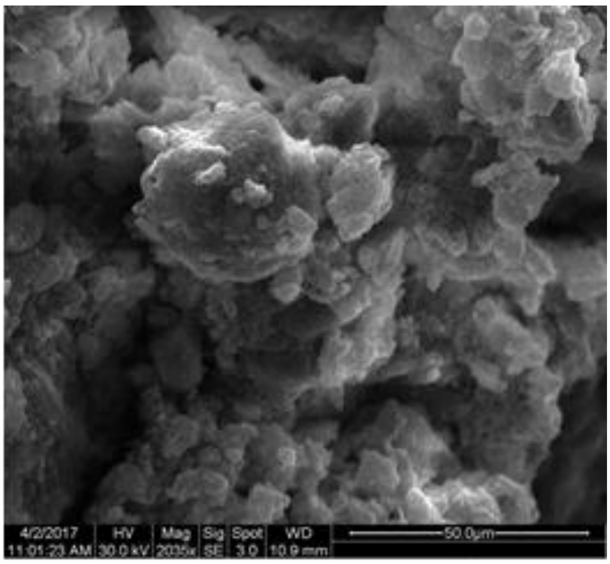
Figure 6. Ultrasonic Time of Concrete Cubes with Different Volcanic Tuff Concentrations at 28-, and 56-Days Ages

3.7. Microstructure Analysis

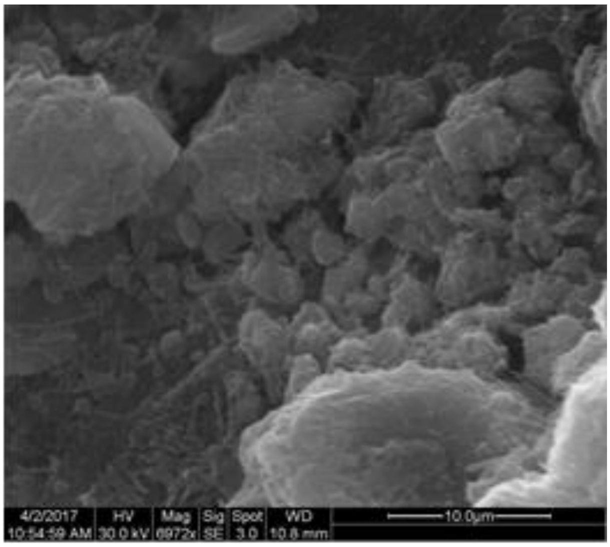
Fig. 7. shows the SEM analysis conducted for the control mix specimen and, the concrete with different ratios of volcanic tuff replacement at 28 days age.

Figs. 7a to 7e show that, the most distinct difference in the microstructure between the different percentages of volcanic tuff as cement replacement concrete mixtures with control mix. According to the comparison between Figs. 7b, 7c with Fig. 7a, the control mix appears to be less porous and denser compared with others, which would contribute to its higher mechanical and durability properties. Volcanic tuff increasing the number of pores in its concrete mixes.

Figs.7d and 7e show SEM images of the concrete specimen prepared with 15, and 20% of the volcanic tuff, respectively. At 28 days age, compressive strengths obtained are lower than control mix. SEM image shows the presence of unreacted volcanic tuff particles. These observations could explain the reduction in compressive strength of these mixes with a relatively high replacement level of Portland cement with volcanic tuff. The main explanation of compressive strengths reduction with 15% and 20% volcanic tuff is due to diminish of cement quantity in this concrete. From Fig. 7, it can be concluded that there was a tendency for a decrease in the number of unreacted volcanic tuff particles, which may be according to the weakly pozzolanic activity of volcanic tuff.



(a)



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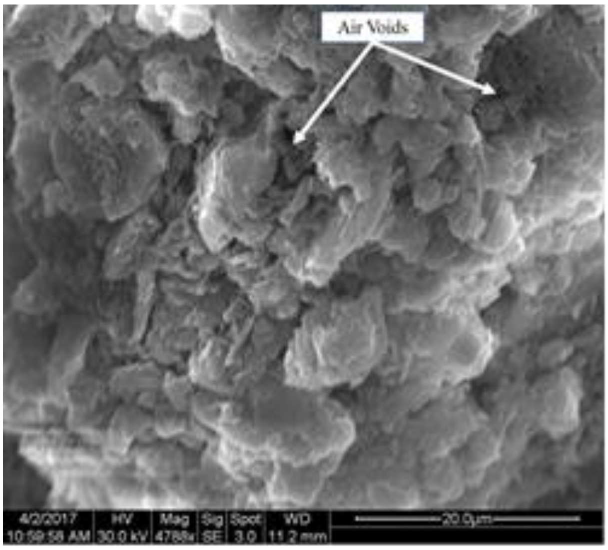

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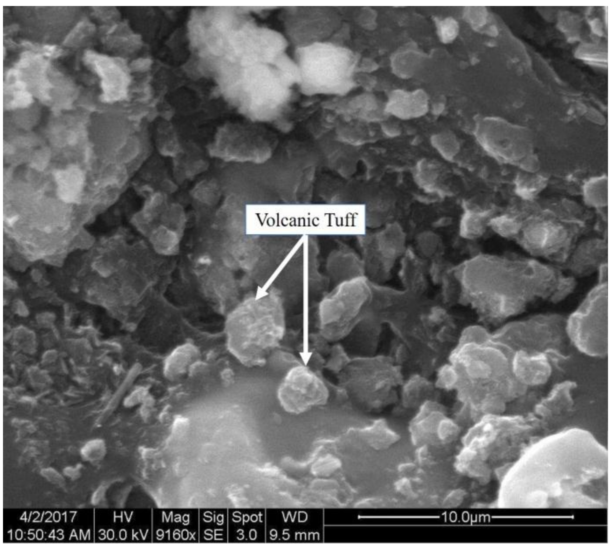
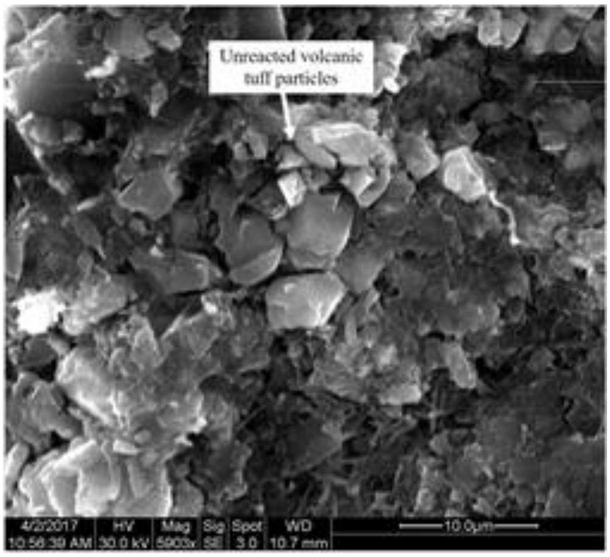


(d)



(e)

Figure 7. SEM Micrograph for: (A) Control Mix, (B) 5% Volcanic Tuff Cement Replacement, (C) 10% Volcanic Tuff Cement Replacement, (D) 15% Volcanic Tuff Cement Replacement, and (E) 20% Volcanic Tuff

4. Conclusions

This study investigated the effect of substituting cement by 5, 10, 15, and 20% of volcanic tuff on properties of concrete at 7-, 28-, and 56-days age. Based on the experimental results, the following conclusions could be drawn:

- According to fresh concrete properties, workability decreased from 8.3% to 66.7% with increasing of volcanic tuff replacement ratios.
- At 7 and 28- days ages, concrete mix without volcanic tuff replacement ratio had the highest value of compressive, and splitting tensile strengths by (22.7, 31.2 MPa), and (1.85, 3.1 MPa), respectively.
- At 28 days age, control concrete mix had the highest value of flexural strength by (3.1 MPa).
- At 56 days age, the higher compressive strength obtained at 10% of volcanic tuff cement replacement by 25.7% (39.2 MPa).
- Regarding the durability properties, at 28 days age, increase of volcanic tuff as cement replacement led to a slightly negative effect on water absorption percentage and ultrasonic pulse velocity compared with control mix (by 19.9% and 2.9%, respectively).
- At 56 days age, the substitution of cement with 10% volcanic tuff, the water absorption percentage and ultrasonic pulse velocity were approximately appropriate (decreased by 5% and 0.88%, respectively).
- At 28 days age, all microstructure images of mixes containing volcanic tuff with different replacement ratios showed more porous compared with control

concrete mix, which directly affects the mechanical and durability properties.

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