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Research Paper

Durability of Ambient Temperature Cured Geopolymer Concrete Containing Waste Tile Powder and Metakaolin

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ABSTRACT

The main objective of this study is to evaluate and compare the mechanical and durability properties of geopolymer concretes that incorporate waste tile powder as a replacement for metakaolin at varying percentages ranging from 0% to 100%. The mixtures were divided into five groups, each with three different levels of sodium silicate to sodium hydroxide ratios of 1, 1.25, and 1.5. Mechanical properties, such as compressive strength, splitting tensile strength, and ultrasonic pulse velocity were considered to study the impact of waste tile powder substitution. Additionally, durability of the mixtures was examined by measuring water absorption, electrical resistance, and accelerated chloride ions migration coefficient. Mineralogy of the geopolymer concrete was analyzed by XRD, and the microstructure was examined using SEM. Results indicate that incorporating 25% waste tile powder as the replacement for metakaolin led to a noteworthy increase in the compressive strength, splitting tensile strength, and ultrasonic pulse velocity of the geopolymer concretes. In addition, the SEM micrographs results indicated that geopolymer concrete with 25% waste tile powder and 75% metakaolin had smaller micro-cracks in the geopolymer matrix. However, when the proportion of waste tile powder exceeded 50%, mechanical strength of the geopolymer concretes declined.

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1. Introduction

Geopolymer concrete is a relatively new, innovative and sustainable engineering material that has many advantages over conventional concrete [1]. Geopolymer concrete has been studied over the past decade as an alternative for sustainable building materials that can minimize carbon dioxide emissions from the construction industry [2].

One of the biggest advantages of geopolymer materials is that they are produced from various natural and industrial alumino-silicates such as metakaolin, fly ash, and blast furnace slag. When alumino-silicates from waste materials are partially replaced for cement, alkali-activated alumino-silicates can be produced [3]. Metakaolin is an alumino-silicate material that is obtained through the calcination of kaolin clay. Bai et al. [4] conducted a study on geopolymer concrete modified with steel slag in which steel slag powder, after grinding, was replace as a part of metakaolin powder. Steel slag powder was replaced by metakaolin in amounts of 10%, 20% and 30% by weight and processed in an environment of 30℃, and the results showed that 10% replacement caused an increase in the compressive and flexure strengths. Kumar et al.[5], replaced 0 to 40% metakaolin in geopolymer concretes containing blast furnace slag and the results showed that 20% replacement improved compressive strength. Metakaolin resulted in a better degree of geo-polymerization and denser pore structure in the samples[6]. However, the calcination process to produce metakaolin contributes to global warming and reduces the availability of natural kaolin, making metakaolin expensive for use in concrete and geopolymer composites. To overcome this challenge, researchers suggest various substitute materials, such as waste products from different industries including red brick waste, rice husk waste, waste paper, and glass waste that can be added as alternatives to metakaolin [7–10].

Due to the large amount of waste tile in the construction industry and the burying of this waste from tile factories and also consumers, the use of this type of waste in geopolymer concrete can be suggested. Large amounts of ceramic waste are produced by ceramic industries every year [11]. Recycling of these wastes can be considered as one of the operational solutions to eliminate their disposal. Ceramic wastes have been investigated as aggregates or a part of aggregates in Portland cement composites [11–13] as well as geopolymer or active alkali composites [14, 15].The results have shown that the waste aggregates of ceramic tiles improved compressive strength, water absorption, and chloride ion penetration. El-Dieb and Kanaan [17] showed that 10% replacement level of ceramic waste powder instead of cement is optimal for improving compressive strength and 40% replacement is optimal for reducing accelerated penetration of chloride ions. Replacing waste tile powder as cement in mortars also showed that due to the pozzolanic reaction of the tile powder, compressive strength increased a due to the silica alkali reaction [18]. The reason for this improvement by pozzolanic reaction was reported to be nucleation and effect of waste tile powder.

Some other researchers used ceramic waste powder as a source of alumino-silicate in multi-component combination with slag and fly ash in active alkali concrete and geopolymer composites [16, 19– 21]. Husein et al. [20] investigated effect of high volume waste ceramic powder on the mechanical properties and microstructure of alkaline active mortars exposed to high temperature. In this research, alkaline active mortars were based on ceramic powder waste, fly ash and blast furnace slag. The results showed that resistance of the proposed mortars under high temperature increased by increasing the content of waste ceramic powder from 50 to 70% [20]. In another research by Abdollah-nejad et al. [21], they showed that partial replacement of 0 to 30% of ceramic waste materials instead of slag, in geopolymer concretes, reduced the compressive strength. Ramos et al. [18], investigated compressive strength and microstructure of geopolymer concretes containing porcelain tile polishing residue as a partial source of alumino-silicate. The highest compressive strength of 72 MPa after 28 days was obtained in the concrete containing 15% of porcelain tile polishing residue and 85% of metakaolin. The results also showed that porcelain tile polishing residue can be used as an alternative source of raw materials for the production of geopolymer concrete. Replacement of metakaolin by 33.3%, 50%, and 66.6 % red ceramic waste, also revealed that by 33.3% replacement, the compressive strength was still comparable to the geopolymer concrete with pure metakaolin [22].

Considering the reviewed literature, comparison of metakaolin as a semi-natural material (requiring 600-700 degrees of heat) with tile powder as a waste material from the tile industry to produce geopolymer concretes is investigated in the present study. Therefore, influence of Sodium Silicate to Sodium Hydroxide ratios (SS/SH) alkali substance concentration on the properties of the geopolymer concretes by their mechanical and durability properties are the main concerns of this research. Moreover, while curing of geopolymer composites require high temperature; ambient temperature curing conducted in the present research is advantageous to reduce energy consumption due to the common curing methods.

2. Experimental program

2.1. Materials

The geopolymer concrete mixture containing waste tile powder (WTP) and/or metakaolin (MK) were prepared using Granulated Blast Furnace Slag (GBFS). The utilized metakaolin was provided from the local mines in Zanjan province (Iran) and the GBFS from Sepahan Cement Company in Isfahan province (Iran). Waste tile powder preparation process is shown in Fig. 1. Table 1 and Fig. 2 present chemical ingredients and appearance of the powders.

Fig. 1. The process to prepare waste tile powder

Table 1. Chemical ingredients of GBFS, metakaolin, and waste tile powder (% weight)

Compound	GBFS	Metakaolin	Waste tile powder
SiO2	32.65	78.04	61.54
Al2O3	8.49	12.90	18.65
CaO	39.74	2.03	2.46
Na2O	1.05	1.93	2.42
K2O	0.884	1.20	2.40
MgO	8.40	0.865	1.13
Fe2O3	0.669	0.827	8.65
LOI	0	1.77	0.888

Fig. 2. Appearance of a. GBFS, b. Waste tile powder, and c. Metakaolin

To demonstrate characteristics of metakaolin and waste tile powder, XRD analysis was performed and results are shown in Fig 3. The XRD patterns reveal that both metakaolin and waste tile powder contain peaks attributed to kaolinite (K), quartz (Q) and mullite (Mu). Presence of kaolinite indicates incomplete calcination, and the peaks corresponding to quartz suggest presence of crystalline particles in the raw materials. The XRD pattern of metakaolin and waste tile powder shows that quartz peak in the range of 27-29 is sharper for metakaolin, while it is wider for waste tile powder that is in the range of 25-30, indicating presence of amorphous particles. Moreover, kaolin and mullite peaks in the XRD pattern of waste tile powder also have wider diffraction range, suggesting presence of amorphous particles.

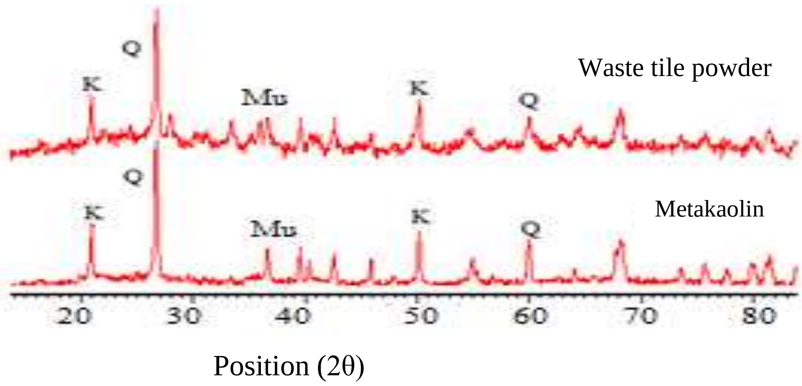


Fig. 3. XRD pattern of Waste tile powder, and Metakaolin

Alkali activators were sodium silicate solution (Na_2SiO_3) with 98% purity and sodium hydroxide (NaOH). Chemical composition of the Na2SiO3 solution was with Na_2O (8.3%), SiO_2 (26.5%), and H2O (65.2%). The sodium hydroxide solution was prepared by dissolving 97% pure NaOH pellets in solid form, in distilled water to produce a 14 Molar solution. The molecular silicate (Ms) modulus, which is the total mass of SiO_2 to the total mass of Na_2O ratio, in the alkali activator solutions was 0.5. The fine aggregate was natural river sand, with a specific density of 2.44 and water absorption of 3.1% and crushed gravel with a maximum size of 19 mm with a specific density of 2.54 and water absorption of 1.8%, respectively. Aggregate grading curve and particle size distribution of MK and WTP are presented in Fig. 4.

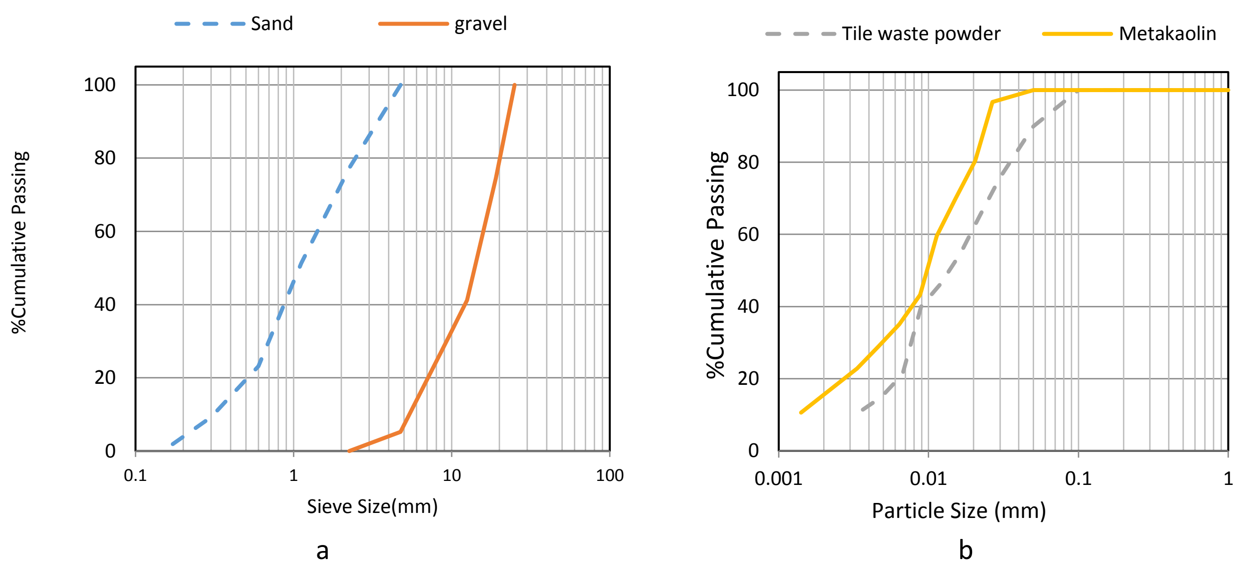


Fig. 4. A. Aggregate grading of coarse and fine aggregate, b. Particle size distribution of MK and WTP

2.2. Mixture preparations

Geopolymer concrete mixtures were considered based on the sodium silicate to sodium hydroxide ratios (SS/SH) of 1, 1.25, 1.5. The binder content for mixtures was kept constant as 400 kg/m^3 including 100 kg/m^3 GBFS. Metakaolin replacement by waste tile powder was at levels of 25%, 50%, 75%, and 100% in unit weight. For all designed mixtures, the total aggregate content was 1680 kg/m^3. Table 2 gives details of the mixture proportion.

Table 2. .Mixture proportion of the geopolymer concretes

Group	ID	Mixture name	SS/SH	Content (kg/m^3)						
				Cement	GBFS	MK	WTP	Water	Na_2SiO_3	NaOH
G1	G1-1	T0MK100-1	1	0	100	300	0	25.2	175	175
	G1-2	T0MK100-2	1.25			300	0		195	156
	G1-3	T0MK100-3	1.5			300	0		210	140
G2	G2-1	T25MK75-1	1			225	75		175	175
	G2-2	T25MK75-2	1.25			225	75		195	156
	G2-3	T25MK75-3	1.5			225	75		210	140
G3	G3-1	T50MK50-1	1			150	150		175	175
	G3-2	T50MK50-2	1.25			150	150		195	156
	G3-3	T50MK50-3	1.5			150	150		210	140
G4	G4-1	T75MK25-1	1			75	225		175	175
	G4-2	T75MK25-2	1.25			75	225		195	156
	G4-3	T75MK25-3	1.5			75	225		210	140
G5	G5-1	T100MK0-1	1			0	300		175	175
	G5-2	T100MK0-2	1.25			0	300		195	156
	G5-3	T100MK0-3	1.5			0	300		210	140
RF	G6	CEMC	0	400	0	0	0		0	0

2.3. Test procedures

For concrete hardened properties, compressive strength accordance BS 1881-part-116-83[23] and Ultrasonic Pulse Velocity (UPV) tests were conducted on 100 mm cube specimens at 28 days. The UPV measurements were carried out on the samples before compression test based on ASTM C 597[24]. Splitting tensile strength was also measured according ASTM C496[25] on 100 × 200 mm cylinders. An electrical resistivity test was performed on three cube specimens of 100 × 100 ×100 mm after 28 days of curing. Two plates of brass as two electrodes were used on saturated surfaces of dry samples to measure the electrical resistivity by ohmmeter. In addition, rapid chloride migration test was carried out on the cylindrical specimens with a diameter of 100 mm and a thickness of 50 mm according to NT BUILD 492 [26]. Water absorption test was conducted according to ASTM-C642[27] at 24 h after casting, they were demoulded and stored in ambient temperature of 25 ± 3 ºC for 28 days. Each result is the average of three test specimens.

To study microstructure properties of the geopolymer concretes including pores and cracks, SEM micrographs were prepared using SEM technique. The X-ray diffraction technique was performed by diffract-meter with Cu K radiation to identify phases present in the hardened MK -WTP geopolymer pastes containing after 28 days of ambient curing. The XRD investigation was conducted for the diffraction angle 2θ, (between 5° and 80°), and had a width of 0.017°. For the XRD, the pastes were separated from the inner core of concrete samples, and passed through sieve No.100.

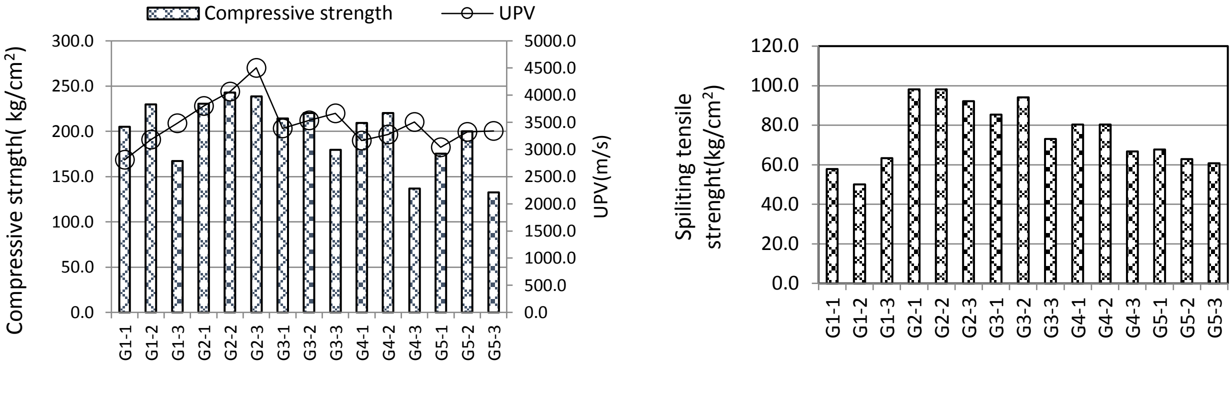
3. Results and discussion

3.1. Durability and mechanical properties

Compressive strength and UPV of geopolymer concrete mixture containing MK and WTP are presented in Fig. 5a. The highest compressive strength was observed in the mixture containing 25% replacement of waste tile powder instead of metakaolin and SS/SH=1.25. Similar results were reported in previous study conducted by Ramos et al.[18]. They found that the highest compressive strength of 72 MPa was achieved after 28 days for a mixture consisting of 15% porcelain tile polishing residue. They attributed this result to the reduction in the crystalline phase of the porcelain tile polishing residue in replacement of metakaolin. The second and third ranks of compressive strength belong to the mixture containing 25% waste tile powder with SS/SH=1.5, and SS/SH=1. The lowest compressive strength was recorded in group G5 mixture with 100% waste tile powder.

Similar to the results of compressive strength, the highest UPV was observed in group G2 containing 25% waste tile powder, but with the value of SS/SH=1.5. This can be due to the resistance of microstructure according to the research by Ramos et al.[18]. Moreover, with the increase of substitution by more than 15%, the silicate/aluminum ratio reached more than 4. The lowest UPV was obtained in group G1 with 100% metakaolin, which shows that despite the increase in the substitution of tile powder, the UPV is decreased and due to the combination of metakaolin and waste tile powder, mechanical characteristics of geopolymer concrete is improved.

As seen in Fig. 5b, The highest splitting tensile strength was observed in the geopolymer concretes containing 25% waste tile powder with SS/SH=1, 25% waste tile powder with SS/SH=1.25, and 50% waste tile powder with SS/SH=1.25. The values were 98.1, 98.1, and 94.1, respectively. The lowest splitting tensile strength was obtained in G1 with 100% metakaolin. This shows that waste tile powder is effective to improve splitting tensile strength of geopolymer concretes.



a b

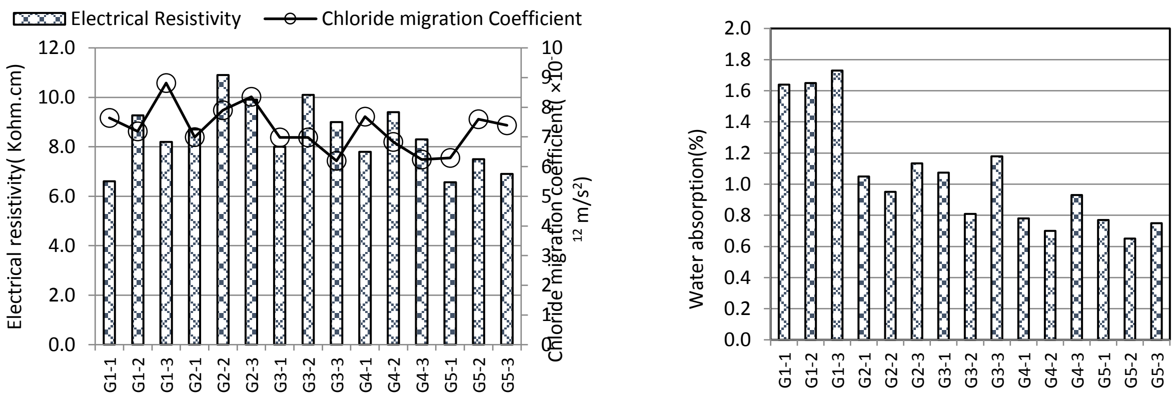
Fig. 5. A. Compressive strength and UPV, b. Splitting tensile strength results of MK-WTP geopolymer concrete samples

Based on the XRD pattern from Fig. 3, the improvement in the splitting tensile strength when replacing up to 50%, can be explained by the fact that the powder contains significant amorphous aluminate particles, which leads to more production of the sodium alumino-silicate gel (N-A-S-H). This finding is consistent with the previous investigation by Kumar and Reddy[28], which reported increased tensile strength in cement concrete.

3.3. Durability Properties

Fig. 6a presents the results indicating that geopolymer mixtures of group 1 including G1-1, G1-2, and G1-3, which contain 100% metakaolin, exhibited the highest water absorption of (1.6%, 1.6% and 1.7%, respectively. In contrast, the lowest percentage of water absorption, equal to 0.7%, was recorded in geopolymer concrete mixtures G5-2 and G4-2. Notably, when the same powder content was used in cement concrete mixture (cement = 400 Kg/m^3), the water absorption was 3.13%, which is about 2 times the highest water absorption and 4 times the lowest water absorption observed in all the geopolymer mixtures. Therefore, geopolymer concrete containing waste tile powder is effective to improve water absorption characteristics.

Fig. 6b presents electrical resistance values and chloride ion migration coefficient of MK-WTP geopolymer mixtures. Results indicate that the highest electrical resistance has been achieved in geopolymer concrete containing 25% tile powder and alkali activator ratio of 1.25. In addition, in the mixtures containing 50% metakaolin and 50% waste tile powder with alkali activator ratio of 1.25; the electrical resistance is slightly lower than G2-2 mixture. The lowest value of electrical resistance was recorded in group G1 containing 100% metakaolin and group G5 containing 100% waste tile powder with alkali activator ratio of 1. The results show that waste tile powder and metakaolin have acceptable performance in the durability of geopolymer concrete.



a b

Fig. 6. A. Compressive strength and UPV, b. Splitting tensile strength results of MK-WTP geopolymer concrete samples

As in Fig. 6 b, the results indicate that chloride migration coefficients are in the range of 6.2 to 8.8 (10^{-12}) m/s^2. The lowest chloride migration coefficient was obtained in geopolymer concrete containing 50% metakaolin, 50% waste tile powder, and alkali activator ratio of 1.5 (G3-3). The second and third ranks of lowest chloride migration coefficients were achieved in G4 (containing 75%

waste tile powder and 25% metakaolin) and G5 (containing 75% tile powder) with an alkali activator ratio of 1.5. Furthermore, the highest chloride ion migration coefficient was recorded in the mixture G1, and G2 with 100% metakaolin and 75% metakaolin with an alkali activator ratio of 1.5, respectively. According to these results, it can be concluded that presence of larger amounts of waste tile powder has beneficial effect on the chloride ion migration coefficient. The results are consistent with water absorption results without considering alkali activator ratio effect, but there are contradictions with the electrical resistance results. Consequently, in the concretes with less water absorption, the chloride ion migration coefficient was lower, but due to the presence of sodium ions in the pore solution, the lower electrical resistance does not indicate reduction in durability.

3.4. Effect of alkali activator ratio

Effect of changes in sodium silicate to sodium hydroxide ratio, as alkali activator ratio, on the mechanical characteristics is presented in Fig. 7a, b, c. As the results show, the highest compressive strength is related to the concretes containing alkali activator ratio of 1.25. According to Zhang et al. [29], when the amount of sodium silicate is increased, new geo-polymerization products may be formed then re-dissolve happens due to the failure of chemical bonds and finally weakening the geopolymer structure occurs. Higher changes in the compressive strength were observed as the SS/SH ratio increased, particularly at higher levels of substitution of waste tile powder. Therefore, in groups G4 and G5, change in the compressive strength is about 40% (50 kg/m^3). While at the substitution level of 25%, this change is about 14% (34 kg/m^3).

Differences in the splitting tensile strengths follows the pattern of "fixed- Reduction” for geopolymer concretes in groups G2, containing 25% waste tile powder, G4 containing 75% waste tile powder, and G5 containing 100% waste tile powder, with increasing SS/SH ratio . It can be noted that pattern of reduction in the change of SS/SH ratio of 1.25, compared to SS/SH ratio of 1.5, is not significant and is less than 10%. The changes in the splitting tensile strengths in group G3, which contains 50% waste tile powder, showed an “increase-decrease” pattern with an increase in SS/SH ratio. This pattern is similar to the pattern obtained for the compressive strength. The highest splitting tensile strength in group G2 is achieved in SS/SH ratio of 1.25. In geopolymer concretes containing 100% metakaolin, the highest splitting tensile strength occurred at an alkali activator ratio of 1.5, which indicates that metakaolin needs more sodium silicate for reactivity. The highest UPV was observed in the mixtures containing an alkali activator ratio of 1.5. By increasing the amount of sodium silicate from 1 to 1.5, the UPV is increased**.**

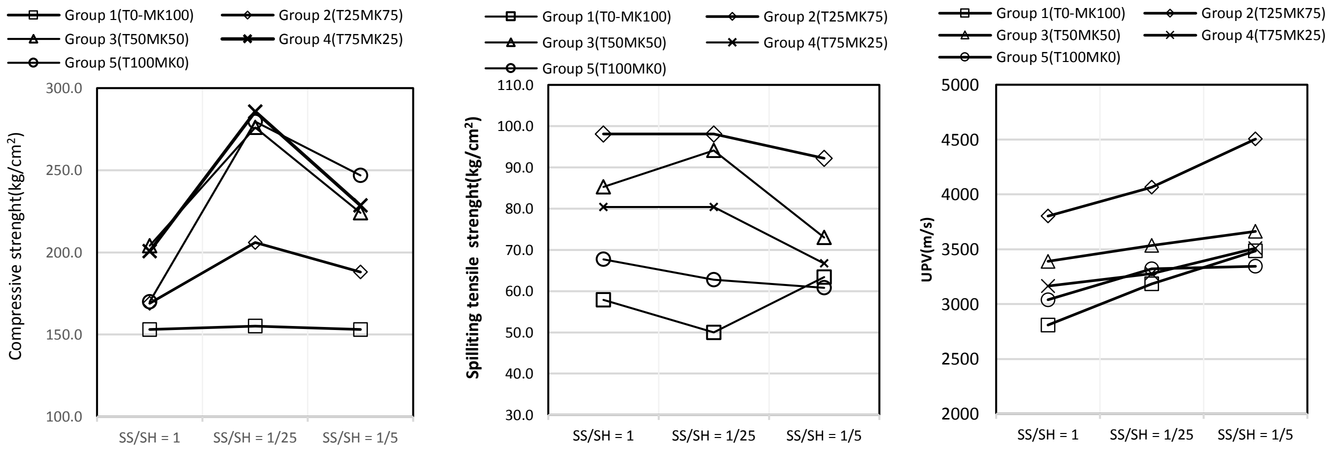


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Fig. 7. The effect of SS/SH ratio on the mechanical properties; a. Compressive strength, b. tensile strength, c. Ultra pulse velocity

Effect of SS/SH ratio on the durability properties is illustrated in Fig. 8. The change in SS/SH ratio on water absorption of different groups with waste tile powder, is almost insignificant. The water absorption of these geopolymer concretes was not significantly affected by changes in the SS/SH ratio. However, in group G3, which consisted of 50% to 50% waste tile powder and metakaolin, a noticeable difference was observed. The lowest level of water absorption (0.8%) was achieved in the mixture with an SS/SH ratio of 1.25. Results of electrical resistivity and compressive strength for the change in SS/SH have almost the same patterns.

Results of chloride ion migration test revealed an "ineffective-increasing" trend in group G1, where 100% metakaolin was used. Chloride ion migration coefficient increased as the SS/SH ratios raised from 1.25 to 1.5. In group G2, which contained 75% metakaolin and 25% waste tile powder, "increase-increase" trend is observed with an increase of the alkali activator ratio. The trend of changes in the chloride ion migration coefficient in groups G3 to G5 follows a "steady-decreasing" pattern. This finding may be attributed to the fact that increasing in the alkali activator ratio leads to the reduction in the rate of chloride ion movement or an increase in the physical absorption of chloride ions.

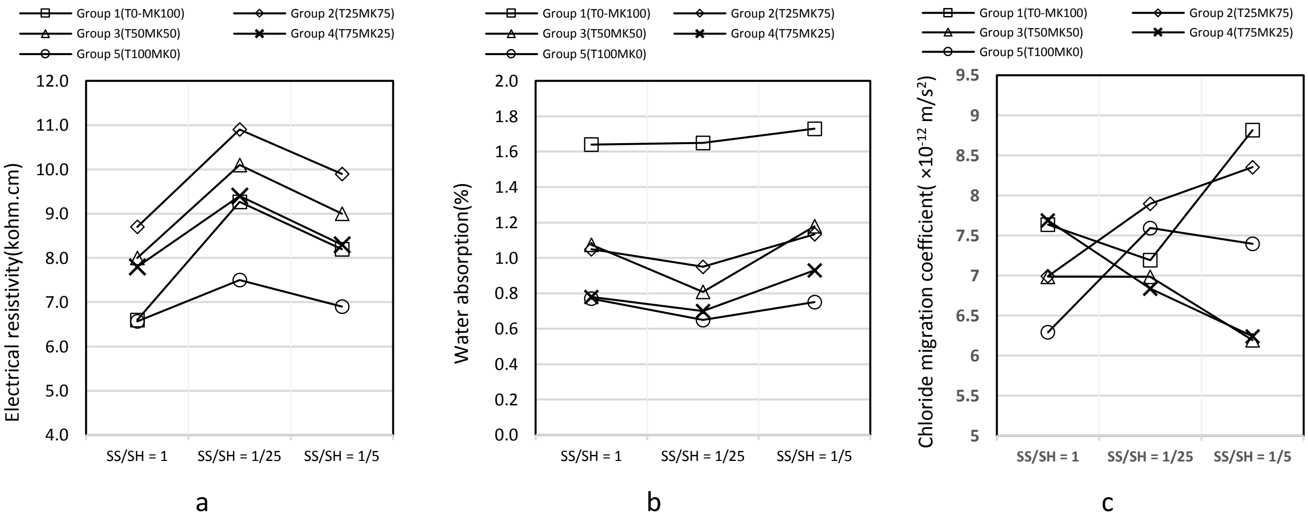

Fig. 8. The effect of SS/SH ratio on durability properties; a. Electrical resistivity, b. water absorption, c. chloride migration coefficient

3.5. Effect of waste tile powder content

Effect of waste tile powder instead of metakaolin on the different mechanical characteristics is presented in Fig. 9. As illustrated in Fig. 9a, compressive strength of geopolymer mixtures decreased with increasing waste tile powder from 0 to 25%. Comparable to this result, Ramos et al. [18] demonstrated that compressive strength of concrete can be enhanced significantly by incorporating waste porcelain tile powder as a substitute, particularly at substitution levels of 0-15%. Results show that compressive strength decreased as the proportion of waste tile powder increased, particularly at levels exceeding 50%. However, the rate of decline was relatively slow between 25% and 75% substitution levels, and became steeper between 75% and 100% substitution levels.

Sarkar and Dana [22] expressed that due to the increase of the SiO_2/Al_2O_3 with the addition of red ceramic powder, when submitting metakaolin in geopolymer concretes, compressive strength improved by 33%., They reported a decrease in the compressive strength, in portions greater than of 66% and 100 % due to the reduction of geopolymer gel formation which is consistent with the results of the current research. They found that the SiO_2/Al_2O_3 within the range of 3.5 to 5 did not have a considerable effect on the strength properties of geopolymer concrete with metakaolin. However, a SiO_2/Al_2O_3 between 1.6 and 3.5 was observed to improve the concrete strength characteristics. Duxson et al.[30] also found that Na_2O/Al_2O_3 plays a crucial role to optimize effect of SiO_2/Al_2O_3 on the properties of geopolymer concrete.

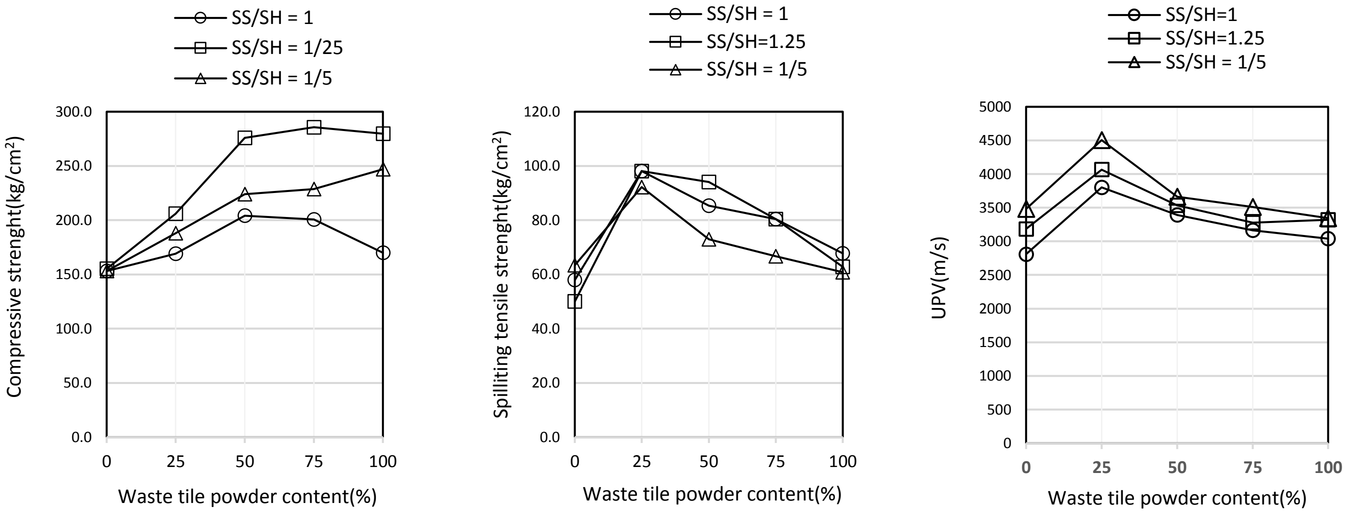

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Fig. 9. The effect of waste tile powder content on the mechanical properties; a. Compressive strength, b. Splitting tensile strength, c. Ultra pulse velocity)

Effect of waste tile powder on the splitting tensile strength is similar to the compressive strength. Fig. 10. illustrates results of compressive strength of studied geopolymer mixtures versus splitting tensile strength.

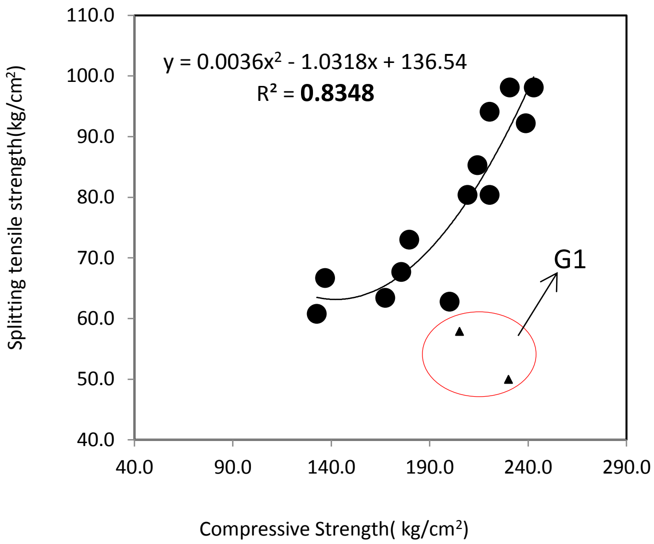


Fig. 10. Compressive strength of MK-WTP geopolymer results versus splitting tensile strength

In group G1 with 100 % metakaolin, there is a reverse pattern for compressive strength and splitting tensile strength, whereas other mixtures have similar trends. It can be concluded that addition of waste tile powder leads to enhancing strength properties of geopolymer concretes through microstructure improvement. Furthermore, in concrete mixtures containing different SS/SH, the highest UPV was observed for 25% waste tile powder, and the UPV increased as the proportion of waste tile powder increased from 0 to 25%. However as in Fig. 9c a subsequent decrease in UPV was observed as the substitution level rose from 25% to 100%.

Effect of replacement level of waste tile powder on the durability properties including water absorption, electrical resistivity, and chloride ion migration coefficient is presented in Fig. 11 and is similar to the effect of compressive strength.

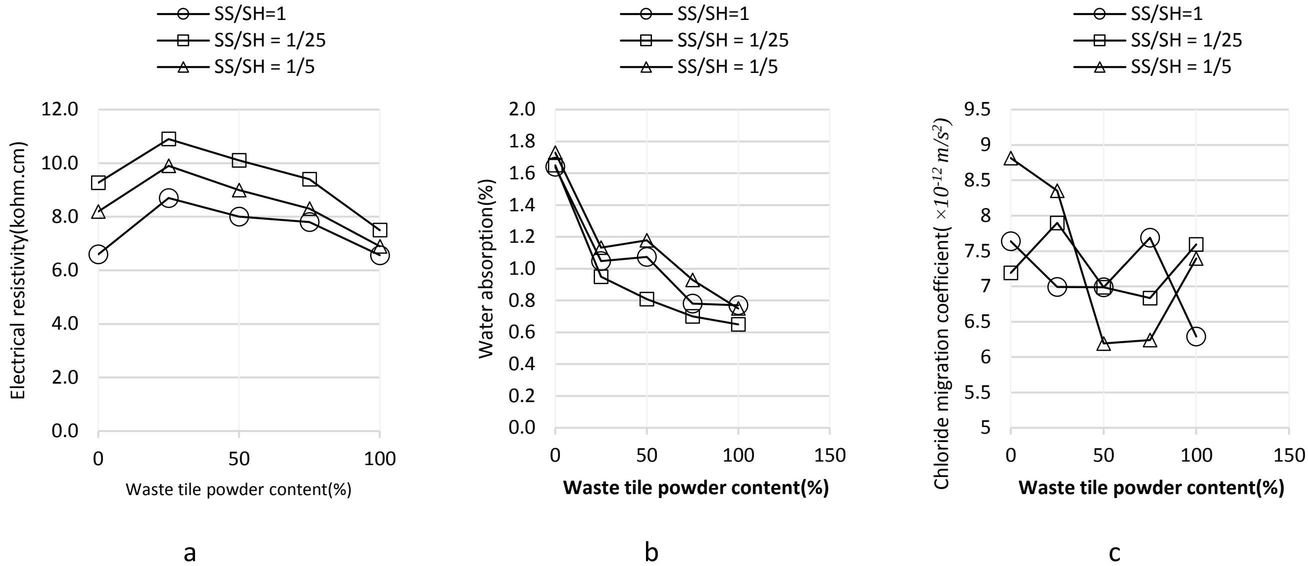


Fig. 11. .The effect of waste tile powder content on durability properties; a. Electrical resistivity, b. Water absorption, c.chloride migration coefficient

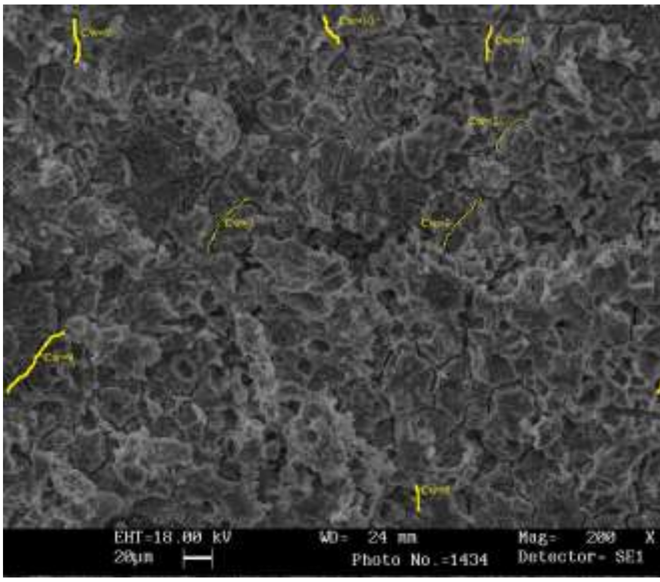
The electrical resistivity values of geopolymer mixtures are decreased with increasing waste tile powder content from 0 to 25%. This observation shows that binary utilization of metakaolin and waste tile powder is effective to improve mechanical characteristics and electrical resistance of geopolymer concretes. Increasing replacement level of waste tile powder and metakaolin increased water absorption of geopolymer concretes, but in amounts greater than 50%, i.e. 75% and 100%, this increase is not significant. The results show that usage of waste tile powder, presumably due to the heat in the tile production process, improved durability properties and water absorption. In groups G5 and G4, where 75% and 100% of metakaolin is replaced by waste tile powder, a significant improvement has been achieved. This can be due to the fineness and reactivity of waste tile powder particles and the heat during tile production.

When metakaolin content in group G1 was 100%, there was an "ineffective-increasing" trend for the effect of alkali activator ratio. This presents that increasing alkali activator ratio from 1.25 to 1.5 increased chloride ion migration coefficients. In group G2, which contained 75% metakaolin and 25% tile powder, an "increase-increase" pattern was observed with the increase of alkali activator ratio. This result signifies that when metakaolin content in geopolymer concretes containing metakaolin and waste tile powder is more than 50%, a higher concentration of alkali activator causes more alumina to dissolve, and therefore the rate of movement of chloride ions is increased. Groups G3 to G5 revealed a relatively steady-decrease pattern. This observation demonstrates that in higher alkali activator amounts, velocity of chloride ion movement is reduced.

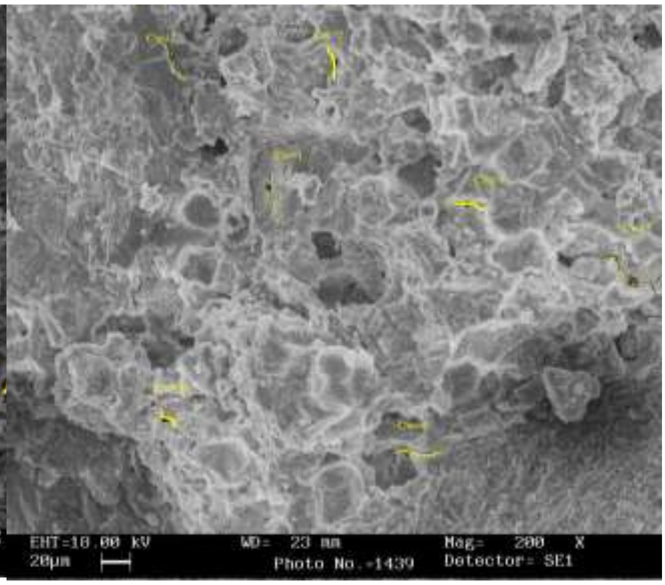
3.6. SEM analysis

Fig. 12 shows SEM micrographs of the geopolymer concretes. The yellow-colored values in micrographs represent crack width in nanometers. The mixture containing 25% waste tile powder and 75% metakaolin has the smallest average pore size of 4.84 µm and the lowest percentage of total pores of 22.32% among all mixtures. According to Fig. 5, the highest compressive and splitting tensile strengths were for the mixture containing 25% waste tile powder. On the other hand, geopolymer concrete mixtures G1-2 with 100% metakaolin, G3-1 with 50% waste tile powder and 50% metakaolin, and G4-1 with 75% waste tile powder and 25% metakaolin have average pore sizes of 6.67, 5.309, and 7.79 µm, respectively.

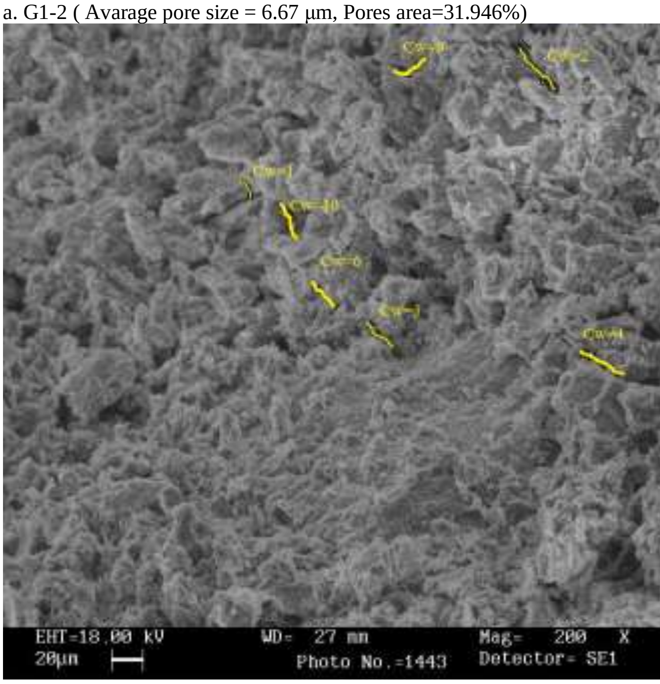
The micrographs analyzed by ImageX software reveal that the geopolymer concrete with 25% waste tile powder and 75% metakaolin exhibits smaller micro-cracks, indicating a denser matrix resulting from geo-polymerization. In contrast, mixtures G1-2 with 100% metakaolin and G4-1 with 75% waste tile powder and 25% metakaolin exhibit more unreacted particles.



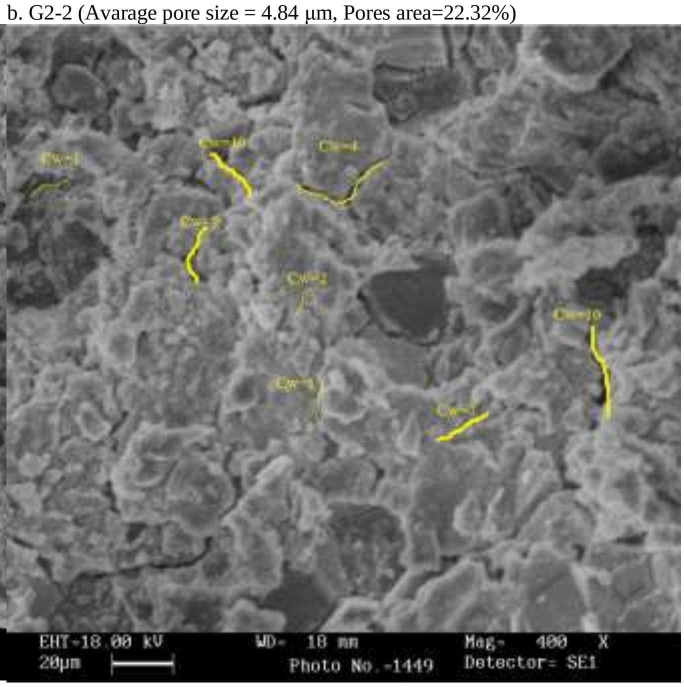
a. G1-2 (Avarage pore size = 6.67 µm, Pores area=31.946%)



b. G2-2 (Avarage pore size = 4.84 µm, Pores area=22.32%)



c. G2-3 (Avarage pore size = 5.309 µm, Pores area=29.93)



d. G2- 4 (Avarage pore size = 7.79 µm, Pores area=28.109)

Fig. 12. SEM micrographs for geopolymer mixtures with SS/SH ratio of 1.25; a. G1-2, b. G2-2, c. G3-2, d. G 4-2

3.7. XRD analysis

Geopolymer mixtures prepared with different amounts of metakaolin and waste tile powder containing alkali activator ratio of 1.25 were selected to identify the XRD patterns. The purpose of this selection was to know the effect of the waste tile powder in a constant amount of alkali activator on the mineralogy of geopolymer concretes. Fig. 13. illustrates the XRD patterns of geopolymer mixtures belonging to groups G1 to G5.

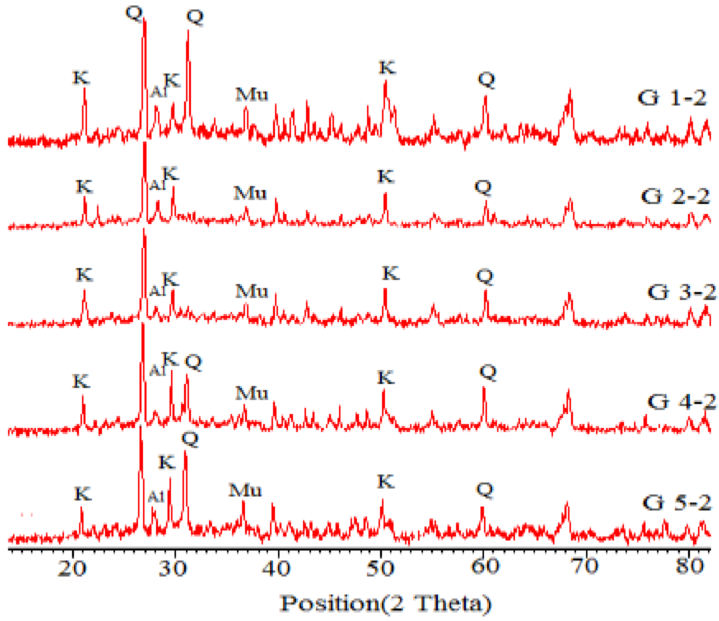


Fig. 13. XRD pattern of geopolymer concretes containing MK and WTP; K= Kaolinite(Al_2O_3 $2SiO_2 \cdot 2H_2O$), Al=Albite ($NaAlSi_3O_8$), Q=Qurtz(SiO_2), Mu=Mullite($3Al_2O_32SiO_2$)

Analysis of the XRD patterns revealed that some of the crystalline phases in the raw materials, such as quartz, mullite, and crystalline kaolinite, did not dissolve completely during the geo-polymerization process. Notably, G2-2 and G2-3 mixtures contained lower concentrations of un-dissolved quartz crystals, revealed improved compressive strength and reduced porosity. Therefore, replacing 25% and 50% waste tile powder improved geo-polymerization. However, the large amount of mullite, quartz and kaolinite peaks in geopolymer mixtures containing 100% metakaolin and 75% and 100% waste tile powder indicate insolubility in the reaction. Less crystalline amounts were observed in the mixture containing 100% waste tile powder, as revealed by the XRD pattern of the waste tile powder that showed presence of amorphous kaolinite particles. The sodium alumino-silicate gel (N-A-S-H) is the principal factor in enhancing mechanical properties [31]. The albite phase peak was identified in the XRD pattern of geopolymer mixtures. The geopolymer concretes displayed a wide diffraction hump, especially in G2-2 and G3-2, with a small amount of peak.

4. Conclusion

The current investigation aimed to explore the impact of waste tile powder and metakaolin on geopolymer concrete by utilizing different alkali activator ratios of 1, 1.25, and 1.5 under ambient curing condition. Various geopolymer mixtures were considered by altering waste tile powder and metakaolin with the substitutions of 25, 50, 75, and 100%. Compressive and splitting tensile strengths, UPV, and durability properties of the mixtures were investigated. In addition, mineralogy of the geopolymer concretes was analyzed by XRD, and their microstructure was observed using SEM. Accordingly, the following conclusions can be obtained from this research,

1- The highest compressive strength in geopolymer concrete with 25% waste tile powder and SS/SH of 1.25, and the lowest compressive strength in the mixtures with 100% waste tile powder and almost similar trends in other mechanical properties, as well as smaller micro-cracks in SEM micrographs of geopolymer concretes with 25% waste tile powder suggest the optimum amount of 25% waste tile powder for this type of geopolymer concrete.

2- The lowest water absorption percentage of 0.7% was recorded in geopolymer concrete mixtures of groups 4 and 5 with SS/SH=1.25. While the highest water absorption percentage were observed in geopolymer mixtures of group 1 which contain 100% metakaolin.

3- The findings suggest that waste tile powder can be a viable partial replacement for metakaolin in geopolymer concrete, but the replacement percentage should be carefully optimized to achieve the desired mechanical properties. Future works could investigate other methods to enhance mechanical properties of geopolymer concrete containing waste tile powder, such as optimizing the SS/SH ratio or incorporating other supplementary cementitious materials.

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