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Performance of one-part alkali activated recycled ceramic tile/fine soil binders

Arass Omer Mawlod*

Department of Civil Engineering, University of Raparin, Kurdistan region, Iraq

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Abstract. Performance of Sustainable materials continues through using of recycled waste construction materials to minimize the utilization of the natural resources. The cement industry is a major source of CO_2 in the atmosphere which is the main cause of global warming. Replacement of OPC with other sustainable cementitious materials has been the most interesting area of researches. This investigation focuses on the properties of alkali-activated mortar with the different replacement ratios of ceramic tile powder (CTP) by fine soil powder (FSP) (0 to 100)% and different molarities of sodium hydroxide concentrations. The experimental program was conducted by examining the compressive strength, water absorption, and water sorptivity. The results showed that the compressive strength of the specimens at age of (28, 56, and 90 days) increases with an increase in the amount of fine soil powder content and decreases at the age of 120 days. Also, minimum water absorption at the age of 90 days was found in the mixes containing 100% fine soil powder. However, fine soil powder replacement had a negative effect on the sorptivity and water absorption values at the age of 120 days. On the other hand, the 12M sodium hydroxide concentration was considered the optimum concentration compared to other concentrations.

Keywords: sustainable alkali-activated mortar; recycled ceramic tile powder; fine soil; mechanical; sorptivity properties

1. Introduction

Binders are the active part of the mortar and concrete; ordinary Portland cement is the most commonly used binder for the construction purposes. The manufacturing process of OPC is responsible for about 7% to 8% of CO_2 emission to the atmosphere which is considered nowadays as a significant contributor to global warming (Andrew 2018). Currently, sustainability in construction materials is considered as the main requirement that encourages researchers to innovate a sustainable construction material as an alternative to conventional concrete. Alkali activated materials can minimize the exploitation of ordinary Portland cement, energy consumption, pollution and the area used to waste landfills, all of that can mitigate global warming (Behera *et al*. 2014). Geopolymer materials production requires less amount of energy as compared to Portland cement production (McLellan *et al*. 2011). Recently, industrial by-product materials are used as a binder to produce alkali-activated concrete with the aid of alkali-activators. Alkali activated materials are developed by mixing sodium silicate and sodium hydroxide with waste materials like fly ash (Fernandez-Jimenez *et al* 2006, Kong and Sanjayan 2010, Sindhunata *et al*. 2006, Jindal *et al*. 2017), granulated slag (Bakharev *et al*. 1999, Shrestha *et al*. 2013), Ceramic waste (Reig *et al*. 2013) and rice husk (Annadurai *et al.* 2020, Bernal *et al*. 2012). And natural materials like metakaolin (Davidovits 1994). These materials contain a huge amount of silica and alumina.

Besides, Ceramic materials indicated approximately 45% of construction and demolition waste formed during the process of destruction; however, ceramic waste was also created from rejected bricks, tiles, and other objects from fabrication (Reig *et al*. 2013). While these materials are largely utilized as a construction backfill or road subbase materials; they can be used as an alternative or replacement cementitious materials or even as base materials for alkali-activated concrete due to the existence of a huge amount of silica and alumina in these materials (Ay and Ünal 2000, Lavat *et al.* 2009, Pereira-de-Oliveira *et al.* 2012, Puertas *et al*. 2008). Approximately 30% of the daily manufacturing volume in the industry and process of applying ceramic materials goes to waste (Senthamarai and Manoharan 2005). Pacheco-Torgal and Jalali (2010) classified the ceramic wastes by production process and type. They proposed that all-ceramic wastes are fired. The time firing (once or twice) is only the difference between the types of ceramic. The fired wastes were produced by construction ceramic factories that utilized only red pastes to create their productions, such as roof tiles, blocks, and bricks. Whereas the fired ceramic waste created from stoneware ceramic such as sanitary ware, and floor (Pacheco-Torgal and Jalali 2010). Therefore, the use of this huge amount of recycled materials as aggregates, activators, and binders could convey high environmental benefits and cost efficiency (Mas *et al*. 2015). Ceramic waste was successfully used up to 35% as pozzolanic admixtures (the particle size of ceramic waste $d90 \leq 0.56$ mm) by Puertas *et al*. (2008); which confirmed the compatibility of utilizing these materials in the production of concrete. Moreover, The geopolymer concrete showed better resistance against corrosion compared to OPC concrete (Shaikh 2014)

The mixture of the sodium hydroxide or potassium hydroxide with sodium silicate or potassium silicate is the

*Corresponding author, Lecturer
E-mail: arass.omer@uor.edu.krd

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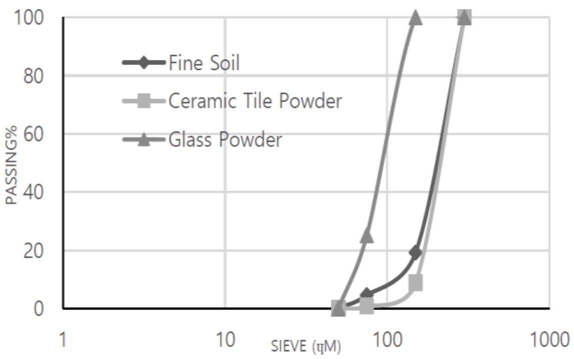

Fig. 1 Particle size distribution of fine soil, ceramic tile, and glass powders

common activator utilized for activating alumina-silicate materials (Shafiq *et al*. 2017). These alkaline solutions are manufactured products. Sodium silicate is produced at high temperatures between 1300-1500°C by melting sand with sodium carbonate (Foletto *et al*. 2006, Kalapathy *et al*. 2002). This process requires a huge amount of energy and also emits dust, nitrogen oxide, and sulphur oxide to the atmosphere (Foletto *et al*. 2006). Which is one of the factors that encourage the researchers to develop one part of alkali-activator.

Karozou *et al*. (2019) examined clay soil that contained a huge amount of silica, alumina, and lime as a geopolymer base material. Mechanical and physical properties were investigated. It was concluded that earthen materials are good options to utilize as geopolymer base material.

Abdollahnejad *et al*. (2018) studied the compressive strength and microstructural analysis of one-part alkali-activated ceramic/slag binders; they concluded that increasing the ceramic content in the mixes decreased the compressive strength. While Rajeswaran *et al*. (2018) Investigated the mechanical and absorption properties of fly ash mortar blended with ceramic waste. It was concluded that the compressive strength and absorption properties were adversely affected by the replacement of ceramic waste powder. Moreover, Rovnanik *et al.* (2016) studied the mechanical properties of blended alkali-activated fly ash/brick powder. They investigated that the mixes containing a higher amount of brick powder showed less compressive strength. The use of glass powder in geopolymer paste was studied by Tho-In *et al*. (2018), they investigated that the highest compressive strength was achieved in case of the fly ash replaced with 20% glass powder. The presence of glass powder improved the composition of the final production of geopolymer concrete (Torres-Carrasco and Puertas 2015). The fine glass was used as an alternative to fine sand (Pan *et al*. 2017), they indicated that the alkalinity of the geopolymer concrete increased with the incorporation of fine glass. However, replacing recycled glass as a replacement of fine river sand is caused to reduce compressive strength (Guo *et al*. 2015). In addition, the durability of geopolymer and conventional concrete was investigated by Alzeebaree *et al*. (2018), they concluded that the geopolymer had superior performance than conventional concrete.

Curing condition has a significant impact on the development of mechanical properties of geopolymer concrete (Patil *et al*. 2014, Abdollahnejad *et al*. 2019). The comparative investigation on one-part alkali activated ceramic tile powder blended with fine soil powder is a remained gap of researches. The novelty of this work arises through producing geopolymer concrete with the incorporation of locally available materials. Ceramic tile waste increases day by day worldwide. In our country a huge amount of ceramic tile waste piled. This investigation examines the feasibility of recycled ceramic tile powder waste in construction applications. In this study, authors would like to examine the use of natural available fine soil as a binder in the production of alkali activated materials.

Although there are some studies concerning the mechanical and durability of one-part alkali-activated binders, very few researches dealing with a comparative investigation on one-part alkali-activated ceramic tile powder blended with fine soil powder that contains a huge amount of silica, alumina, and lime were conducted. This study aims to investigate compressive strength, water absorption and water sorptivity properties of alkali-activated ceramic tile binder blended with variance ratio of fine soil powder, and the influence of alkali concentrations on compressive strength, water absorption and sorptivity of ceramic tile powder-based alkali-activated mortar was reported.

Table 1 The chemical composition of fine soil, ceramic tile, and glass powders

Materials	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	Fe2O3	SO_3	Mn
Ceramic tile	33.239	8.158	23.972	4.618	5.273	1.148	2.270	0.255	19.587
Fine Soil	13.926	4.490	60.277	5.892	0.762	0.564	2.737	0.187	10.262
Glass Powder	40.585	0.956	6.364	10.858	27.059	0.172	0.140	0.206	13.097

2. Materials and methodology

The binder materials for alkali-activated mortar consists of (ceramic tile powder, fine soil, and glass powder), these waste materials were collected, cleaned, dried, and crushed to powder. The powder materials were available in Rania city, Sulaimaniyah, Iraq. The ceramic tile and glass powders were obtained from recycled ceramic tile and glass. The fine soil was naturally available and taken from an area around Rania city. All powder materials were passed through sieve 300μm and used as a binder in the production of mortar mixes in the current study. The particle size distribution of the powders was shown in Fig. 1. The chemical composition of powder materials obtained from the XRF test as illustrated in Table 1.

Locally available fine river sand with specific gravity 2.64 according to BS 882-1973 was utilized as fine aggregate in the production of alkali-activated mortar. The used alkali-activator solution consists of sodium hydroxide (NaOH) in flakes with purity (99%). The flakes of NaOH were dissolved in the tap water and the required concentration of NaOH solution was prepared 24 hrs. before use in the production of alkali-activated mixes.

Table 2 Mix proportion of the alkali-activated mortar (Kg/m^3)

Mixes	Proportion of binders	Ceramic Tile Powder	Fine Soil	Glass Powder	Fine Sand	NaOH Molarity	NaOH Solution	Binder/ Solution
M1	C100-S0	1215	0	233	467	12	580	0.40
M2	C80-S20	972	243	233	467	12	580	0.40
M3	C60-S40	729	486	233	467	12	580	0.40
M4	C40-S60	486	729	233	467	12	580	0.40
M5	C20-S80	243	972	233	467	12	580	0.40
M6	C0-S100	0	1215	233	467	12	580	0.40
M7	C100-S0	1215	0	233	467	16	580	0.40
M8	C100-S0	1215	0	233	467	14	580	0.40
M9	C100-S0	1215	0	233	467	10	580	0.40
M10	C100-S0	1215	0	233	467	8	580	0.40

The experimental study consists of two series of mixes. First, six mixtures were designated of ceramic tile binder replaced with different percentages of fine soil powder (0%, 20%, 40%, 60%, 80%, and 100%). By using a constant concentration (12M) of NaOH solution. The other four mixes were conducted to evaluate the influence of various NaOH concentrations (8, 10, 14, and 16) on mechanical and durability properties of the alkali-activated ceramic tile binder.

3. Test procedure

3.1 Compressive strength

The compressive strength test of the specimens was conducted according to the ASTM standard for cement mortar (ASTM C109 standard 2008). Three identical specimens for each mix were tested by a digital compression machine having a maximum load capacity of 2000kN. The average value of the three specimens was measured and recorded.

A constant ratio of 0.4 (binder/solution) was utilized in the current study. Glass powder and fine sand were used with ratios of 10% and 20% of the total weight respectively. Table 2 presents the mix proportions of the alkali activated mortar mixes.

Sodium hydroxide flakes were dissolved in tap water to obtain the required concentration of the solution for the alkali-activated mortar. The binder materials (Ceramic tile, fine soil, and glass) powders were mixed. The mixed binder was blended with fine sand. The alkaline solution was then added to the mix. The fresh mix was poured into the moulds with size (25×25×25) mm in two layers. Each layer was manually compacted to eliminate the entrapped air. 126 mortar specimens were prepared; for each test, three identical specimens were prepared. To avoid the loss of internal moisture, the specimens were covered by a plastic bag. After 24 hrs. of casting, the specimens were demoulded and oven cured at 45°C for a period of 24 hrs. The mechanical properties represented by compressive strength for the test specimens were evaluated at the ages of 28, 56, 90, and 120 days. While the durability properties indicated by water absorption was conducted at the ages of 90 and 120 days and water sorptivity test was evaluated at the age of 120 days.

3.2 Water absorption

Water absorption is the ability of the material to absorb water and retain under specific conditions. The durability of materials can be evaluated by conducting a water absorption test. In this study, three specimens for each mix were dried to a constant mass in an oven at 105°C for 24 hrs. After that, the specimens were kept cooled to room temperature. The specimens were immersed in water for 24 hrs. to obtain the saturated mass of the specimens. The increase in mass to the dry mass by percentage is called the water absorption.

$$\text{WA\%} = \frac{M2 - M1}{M1} * 100$$

Where: WA is the water absorption; M1 and M2 are the oven-dry mass and the saturated mass of the specimen, respectively.

3.3 Water sorptivity

The water sorptivity is the ability of the material to absorb water by suction. It is one of the tests related to the durability of the material to evaluate the ingress of water through the material. The water sorptivity of alkali-activated mortar was tested according to ASTM C1585 (2011) standard. Three (25×25×25) mm specimens from each mix were used to indicate the water sorptivity of the alkali-activated specimens. The specimens for each mix were dried to a constant mass at 105°C in an oven. After drying, the specimens were taken out and cooled to room temperature then coated with silicone sealing to avoid entering of water from the sides. After that, they were kept in water with a depth, not more than 4mm above the bottom of the specimens. The wetted height of the specimen was evaluated by dividing the increase of the mass of the specimen weighed at different time intervals to the bottom surface area of the specimen and density of water. These values were plotted versus the square root of time and the sorptivity index of the mortar was calculated by the slope of the best fit line.

4. Results and discussion

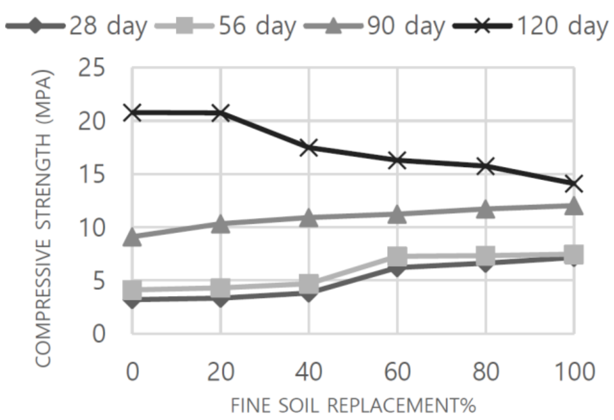

Fig. 2 The compressive strength of the ceramic tile powder/fine soil-based alkali-activated mortar

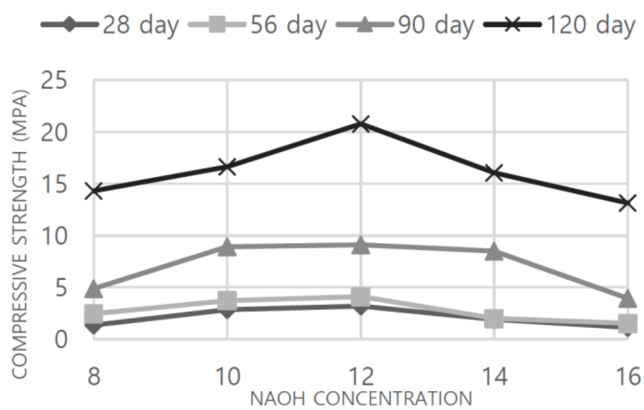

Fig. 3 Effect of Sodium hydroxide concentration on compressive strength of ceramic tile powder-based alkali-activated mortar

4.1 Compressive strength

Fig. 2 illustrates compressive strength results for alkali-activated mortar at the ages of 28, 56, 90, and 120 days. It is indicated that the compressive strength was increased with an increase of the fine soil content up to the age of 90 days. The fine particle sizes and the higher amount of Calcium oxide (CaO) content of fine soil powder compared to ceramic tile powder as shown in Fig. 1 may be the reason for the improvement of the compressive strength compared to ceramic tile powder. The strength improvement due to finer grains of the powder was investigated in the previous studies (Szabó *et al*. 2017). The influence of the amount of CaO content on the mechanical and durability of concrete was investigated by Alzeebaree *et al*. (2019); Mohammedameen *et al*. (2019); they indicated that the compressive strength at the ages of 28 and 90 days of concrete was increased with an increase in CaO amount content of the binder materials. However, the compressive strength of ceramic tile powder-based mortar was more than the fine soil-based mortar at age of 120 days. The compressive strength of alkali-activated mortar at the age of 120 days was decreased with an increase in fine soil replacement ratio as shown in Fig. 2. The compressive strength of ceramic tile powder improvement most probably was due to the dense microstructure and the high amount of SiO2 compared to fine soil powder. These results indicated that fine soil powder can be utilized instead of ceramic tile powder for early age high strength construction requirements.

On the other hand, the compressive strength of alkali activated mortar was affected by the variation of the concentration of alkali-activator solution (NaOH) as shown in Fig. 3. The compressive strength of alkali-activated mortar improved with an increase in the concentration of NaOH solution up to the concentration of 12M. However, the concentration of NaOH more than 12M (14M and 16M) had a negative effect on the compressive strength of alkali-activated mortar. So it can be concluded that the optimum concentration regarding the compressive strength for the current study was 12M. The previous studies also indicated that the best concentration of alkali solution for the geopolymer mortar was 12M (Adak *et al*. 2014).

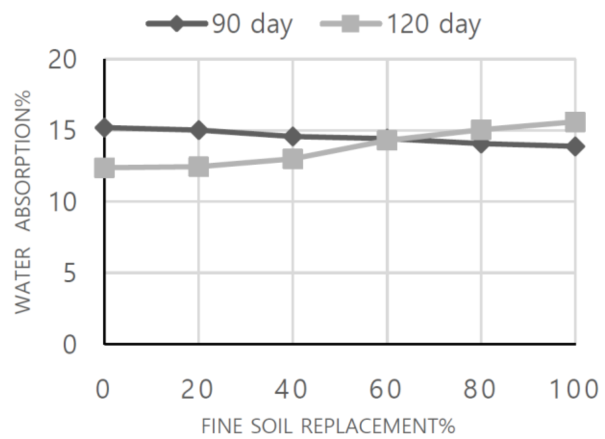

Fig. 4 Water absorption of the ceramic tile powder/fine soil powder-based alkali-activated mortar

4.2 Water absorption

The durability of alkali-activated mortar in the current study is represents by the evaluation of both water absorption and sorptivity performance. The open porosity of the mortar is the significant factor that affects the durability and water absorption performance. The water absorption results from the tested specimens are shown in Fig. 4. It can be noted that the water absorption of alkali-activated mortar decreased with an increase of the amount of fine soil powder content in the mixes at the age of 90 days. The finer particle sizes of fine soil powder compared to ceramic tile powder as shown in Fig. 1 decreased the porosity and made the microstructure denser. However, the water absorption of the tested specimens at the age of 120 days increased with an increase in the amount of fine soil powder content in the mixes. This result well corresponded with the compressive strength improvement for the mixes containing ceramic tile at age of 120 days. It is the result of high activity of ceramic tile powder and fully activated particles that caused a reduction in the amount of open porosity and made a denser microstructure which led to a reduction in water absorption.

Furthermore, it was noted that the water absorption of alkali-activated mortar was significantly influenced by the variation of the concentration of alkali-activator solution

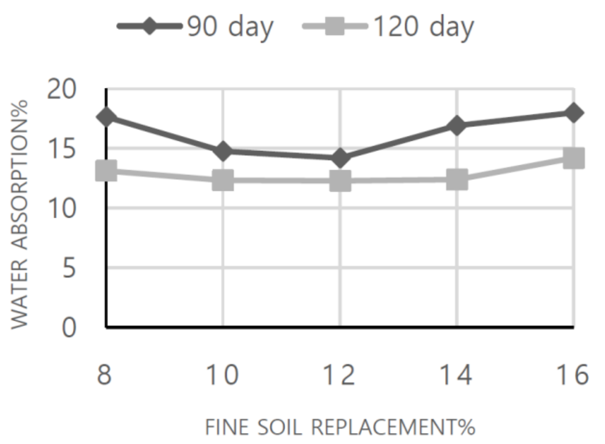

Fig. 5 Effect of Sodium hydroxide concentration on water absorption of ceramic tile powder-based alkali-activated mortar

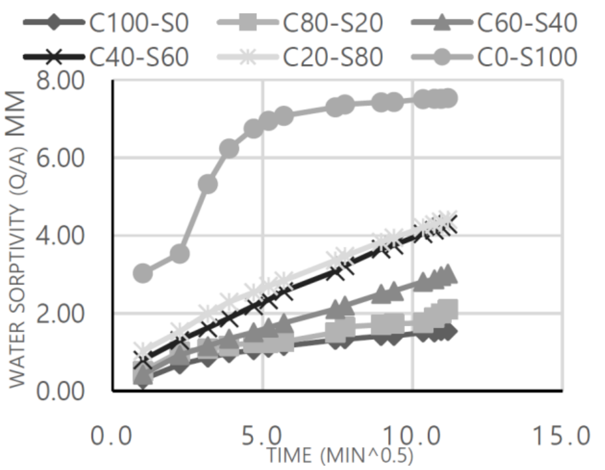

Fig. 6 The water sorptivity of the ceramic tile powder/fine soil powder-based alkali-activated mortar

(NaOH). The water absorption of the test specimens was decreased with an increase in the concentration of alkali-activated solution from 8M to 12M. The increase of the concentration of alkali solution from 12M to 16M shown a negative effect on water absorption performance. The results well corresponded with the impact of NaOH molarity variation on compressive strength. This phenomenon may be due to better formation of gel, denser microstructure, and less open porosity in the concentration of 12M compared to other concentrations as shown in Fig. 5.

4.3 Water sorptivity

The capillary structure of the alkali-activated mortar was evaluated through the sorptivity test. The sorptivity test was conducted at the age of 120 days and the results were shown in Fig. 6. It can be reported that the water sorptivity of alkali- activated mortar was increased with an increase in the amount of fine soil powder content in the mixes. The results well corresponded with compressive strength and water absorption. The microstructure of the specimen containing ceramic tile powder at the age of 120 days was

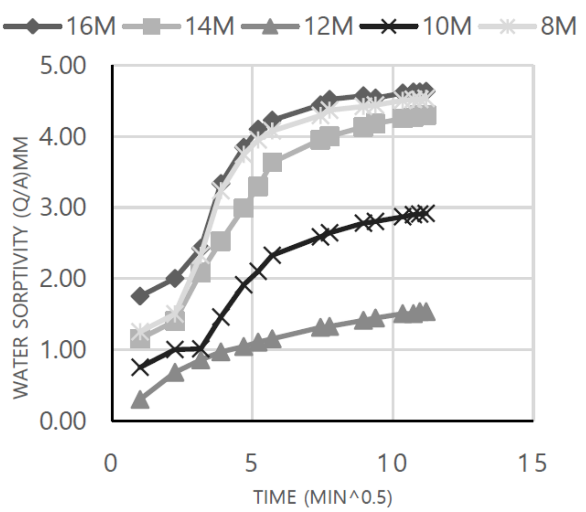

Fig. 7 The effect of Sodium hydroxide concentration on water sorptivity of ceramic tile powder-based alkali-activated mortar

denser than the specimen containing fine soil.

Simultaneously, the water sorptivity of alkali-activated mortar was significantly affected by the variation of the concentration of alkali solution as shown in Fig. 7. It was indicated that the water sorptivity decreased with an increase in the concentration of alkali-activator solution from 8M to 12M. However, the water sorptivity of the test specimen increased in the case of increasing the concentration of alkali solution from 12M to 16M.

5. Conclusions

In this study, the combined influence of binder replacement and concentration of alkali-activated on the hardened state performance of the one-part alkali-activated mortar was investigated. General findings were summarized as follows:

- The outcomes indicated that the replacement of ceramic tile powder with fine soil powder has a positive effect up to the age of 90 days and a negative effect after 90 days. The results at the age of 28, 56, and 90 days for each mix are enhanced both mechanical and durability properties.
- Fine soil powder can be used instead of ceramic tile powder for accelerating strength construction applications.
- As expected, the effect of fine soil powder on the mechanical and durability properties is similar for all mixes.
- The concentration 12M of alkali activator solution is the optimum concentration compared to the other concentrations. The use of concentration 12M was led to an optimum chemical reaction during the mix and better microstructure.
- The particle sizes of fine soil powder and the high amount of CaO content compared to ceramic tile powder may be the reason that the compressive strength was increased with an increase of the fine soil powder

content up to 90 days' age. Whereas the compressive strength decreased at the age of 120 days.

• The durability properties represented by water absorption and sorptivity of the alkali-activated mortar are also improved at the age of 28, 56, and 90 days. This enhancement may be due to the denser microstructure for the mixes containing fine soil powder compared to the microstructure of the mixes containing ceramic tile powder.

• The water absorption and sorptivity of alkali-activated mortar increase with an increase in the concentration of sodium hydroxide from 8M to 12M.

• The properties of alkali-activated mortar were negatively affected by the concentration of alkali solution above 12M (14M and 16M).

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