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Thermal and mechanical characteristics of pozzolana concrete

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Abstract:
To improve the thermal conductivity and compressive strength of concrete, the use of pozzolana aggregate as a partial substitution for natural aggregate in the concrete mix was examined. Natural pozzolana (volcanic tuff) deposits abound in Al Hale Mountain, Tafila, Jordan. In this study, concrete with natural aggregate was employed as a control sample to compare with pozzolana concrete. Twenty-five concrete specimens were produced by replacing 0%, 10%, 20%, 30%, and 40% of natural aggregate with five different aggregate sizes of 2.36, 4.75, 9.50, 12.50, and 19.00 mm. Thermal conductivity and compressive strength were measured for concrete cubes with dimensions of 100 x 100 x 100 mm. Results indicated that aggregate size had no substantial influence on the thermal conductivity of concrete for different pozzolana substitution percentages. The best results are achieved with a 30% pozzolana substitution and a pozzolana aggregate size of 9.5 mm, where the thermal conductivity decreases from 1.78 W/m.^{o}C to 0.53 W/m.^{o}C with a 70% reduction, while the compressive strength increases from 9.10 MPa to 14.56 MPa with a 60% increment. The use of pozzolana aggregate as a partial substitution of natural aggregate in structural materials provides the desired thermal conductivity and compressive strength as green concrete. As a result, the energy required for cooling and heating in buildings is reduced, resulting in energy conservation.

Key Word*: Pozzolana concrete; natural aggregate; pozzolana aggregate; thermal conductivity; compressive strength.*

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I. Introduction

Nowadays, energy costs are a serious economic problem that requires finding alternatives and solutions to avoid financial crises. Refrigeration, heating, and air conditioning systems each account for significant shares of a building's energy use since they are in constant use. Building materials have a significant impact on how much energy is used to meet the heating and cooling demands. Concrete is one of the most widely utilized construction materials, particularly in developing countries [1]. The use of surrogate aggregates as a partial substitution of natural aggregate in the concrete mix could make concrete more thermally and mechanically efficient, which contributes to reducing energy costs. Generally, a low thermal conductivity value and a high compressive strength value are often referred to as good energy efficiency in buildings [2]. Concrete's thermal conductivities can range from 0.6 W/m.^{o}C to 3.6 W/m.^{o}C depending on the moisture content, kind of aggregates, temperature gradients, and testing method [3].

Energy efficiency in buildings can be enhanced passively by minimizing the amount of heat transferred between buildings and their environments. The measure of heat loss through a material, referred to as the thermal conductivity value, is also used as a way of describing the energy efficiency of a building. It is possible to reduce the thermal conductivity of concrete by partially substituting one of the constituents of concrete with thermally insulating additives such as pozzolana aggregates or glass bubbles [4]. Thermal conductivity is an important characteristic for quantifying and interpreting the thermal insulating performance of a material like concrete. However, it can be influenced by several factors, such as temperature gradients and moisture content [5-7]. Some researchers employed numerous steady-state and transient approaches for thermal conductivity measurements, including [8, 9], and the test conditions also had an impact on the obtained results [10]. The transient hot-wire method was employed to assess the thermal conductivity of the hollow clay bricks, and a new brick design was proposed with a 24% thermal performance improvement [11]. The transient parallel hot-wire method was used by [12] to measure the thermal conductivity of ultra-high performance concrete at different temperatures ranging from 20 ^{o}C to 900 ^{o}C. The thermal conductivity varied between 0.3 W/m.^{o}C and 3.18 W/m.^{o}C. Experimental results showed that high temperatures greatly affect the thermal properties of ultra-high performance concrete with different coarse aggregates. An experimental study was conducted by [13] to assess the influence of surrogate aggregates on the thermal conductivity of concrete at various temperatures. In place of natural aggregates, glass bubbles and lightweight particles were used to create five thermally insulated concrete prototypes. Surrogate aggregates effectively reduce thermal conductivity to about 1.25 W/m.°C at room temperature, compared to natural concrete's thermal conductivity of about 2.25 W/m.°C. The thermal conductivity of the concrete mix was not affected by aggregate size; fine, medium, and coarse aggregates all produced similar results. Theoretical and experimental studies on the apparent thermal conductivity of pozzolana concrete were investigated by [14]. Natural pozzolana was used as a basic component in building materials, namely pozzolana concrete, that contained pozzolana as a porous material with adequate mechanical performance, such as compressive strength. Natural pozzolana was used as a basic component in building materials such as concrete, which contained pozzolana as a porous material with adequate mechanical properties such as compressive strength. Findings indicate that it is economically advantageous to use pozzolana aggregates as partial substitutions of natural aggregates in the concrete mix as hydraulically active additions to obtain the desired thermal conductivity and compressive strength. A further experimental study was carried out by [2] to assess the effect of corn cob ash (CCA) blended cement on the thermal conductivity of the concrete mix. Nine classes of CCA blended cement were employed with the CCA content ranging from 0% to 25%, where 0% CCA substitution was referred to as the control sample. The cement to sharp sand ratios utilized in the mix were 1:1, 1:2, and 1:3, with a water-to-binder ratio of 0.26 to 0.29. Test results indicated that for a 1:1 mix proportion, the thermal conductivity decreases from 1.80 W/m.°C to 0.69 W/m.°C when the CCA percentage substitution increases from 2% to 25% compared with the control value of 2.40 W/m.°C.

Several studies have been undertaken to investigate the effect of replacing one or more concrete constituents and aggregate sizes on the compressive strength of concrete. According to several studies, compressive strength is one of the most important properties of concrete. Maintaining sufficient levels of mechanical performance of concrete, such as compressive strength, has a significant effect on the performance characteristics of the concrete mix and ensures the overall quality of the finished product [15-18]. The effects of the size of aggregate (12.5, 19.0, 25.0, 32.0, 38.0, and 50.0 mm) and cement content (150, 200, 250, 300, 350, and 400 kg/m^3 of concrete) on the compressive strength of brick aggregate concrete were reported by [16]. According to test data, the compressive strength of concrete improves as the cement content of the concrete increases. Results revealed that the compressive strength of concrete increases with the increase in aggregate size for a cement content of 150 kg/m^3. However, for concrete with a cement content of more than 150 kg/m^3, the compressive strength increased with the increase in aggregate size up to 25 mm and decreased as the aggregate size increased beyond 25 mm. The influence of nano and micro silica on concrete compressive strength and pozzolanic activity at different substitution percentages and two tested ages was studied by [17]. Test results revealed that nano-silica had more impact on the compressive strength of concrete than micro-silica for all tested ages. At 7 days of age, the greatest compressive strength improvement ratios were around 33% for a 3% nano-silica mix and 7% for a 15% micro-silica mix at 90 days of age for a 3% nano-silica mix. A further experimental study was carried out by [19] to investigate the effects of the variety and content of three natural pozzolana aggregates; black pozzolana, gray pozzolana, and red pozzolana on concrete. Different concrete mixes were prepared by using natural pozzolana to replace 25%, 50%, and 100% of natural aggregate by volume. Results indicated that the density of concrete dropped as the amount of pozzolana aggregate increased, which varied based on the type of pozzolana aggregate utilized. The variety and content of the pozzolana aggregates had a significant impact on the properties of concrete based on the characterization of pozzolan aggregate. The substitution of natural pozzolana at 100% by black pozzolana, gray pozzolana, and red pozzolana aggregates led to a decrease in the thermal conductivity of about 67%, 62%, and 55%, respectively, whereas compressive strength was reduced by about 26.4%, 28.6%, and 32.8%.

Pozzolana is the trade name for volcanic tuff, a type of igneous rock. Natural pozzolana (sedimentary, volcanic, and metamorphic rocks) deposits abound in Al Hala Mountain, Tafila, Jordan, as shown in Figure 1. The use of pozzolana aggregate in the concrete mix as a partial substitution for natural aggregate can be an effective insulator with adequate mechanical properties.

The purpose of this study was to find the right amount of pozzolana aggregate content and the right size of pozzolana aggregate to achieve the necessary thermal conductivity and compressive strength. Therefore, the variation of thermal conductivity and compressive strength with the variation of aggregate size and pozzolana aggregate content was evaluated by making concrete cubes of size 100 x 100 x 100 mm specimens using five different pozzolana aggregate contents and five different sizes of pozzolana aggregate. In this work, the thermal conductivity and compressive strength of pozzolana concrete were investigated to demonstrate its insulating and mechanical properties.

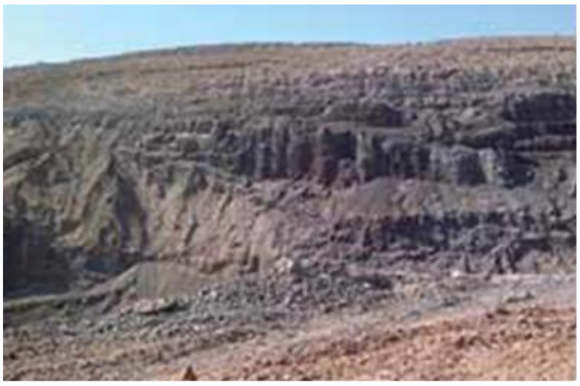

Figure 1: Photo from Al Hala Mountain showing natural pozzolana in Tafila, Jordan.

II. Test specimen preparation

All the materials used in this study are commonly available in Tafila, Jordan. Pozzolana aggregates with a density of about 1.0 g/cm^3 were extracted by the crushing of natural pozzolana. The natural pozzolana was crushed using a jaw crusher device, and the required amount of aggregate for each nominal (2.36, 4.75, 9.50, 12.50, and 19.00 mm) size was obtained by using a sieve shaker device. After crushing, sieve analysis was performed for each of the five nominal aggregate sizes using the ASTM standard sieves. Figure 2 displays the jaw crusher device and the sieve shaker device.

Figure 2: (a) Jaw crusher device. (b) Sieve shaker device.

The specimens were demolded after 24 hours of casting and then submerged in water for 28 days. All the side surfaces of the specimens were further smoothed to ensure that a uniform axial compression load was conducted across the whole cross-sectional area. The particles that were smaller than 2.36 mm were separated from the pozzolana aggregate mass for rejection. Natural tap water was used in this study, which was clean and drinkable. The cubical concrete specimens for this study were cast and measured to achieve accuracy in measurement. The concrete specimens were nominally 100 x 100 x 100 mm in size. Table 1 presents the concrete mix ratios in this study, which are 1:2:4 for cement, sand, and aggregate. The water-cement ratio of the concrete mix was kept at 0.5 for all concrete specimens. Water absorption was about 5-15% for all specimens.

Table 1: Concrete mix details.

Pozzolana's aggregate substitution percentage (%)	**Mass of constituents (kg)**			
	Cement	**Sand**	**Natural aggregate**	**Pozzolana aggregate**
0	10	20	40	0
10	10	20	36	4
20	10	20	32	8
30	10	20	28	12
40	10	20	24	16

The transient hot-wire method using a Quick Thermal Conductivity Meter (QTM-500) device was used to measure thermal conductivity for concrete specimens. This device measures thermal conductivity values between 0.023 W/m.°C and 12 W/m.°C (standard probe) with an accuracy of ±5% and a reproducibility of ±3%, according to the operation manual of the QTM-500 [20]. The measurement results appear after 60 seconds of placing the probe on the sample surface at temperature equilibrium. The applicability of the method to concrete, ceramic, brick, rubber, plastic, glass, fabrics, paper and other construction materials using its various probe sensors is remarkable. The thermal conductivity of concrete specimens was tested at room temperature using QTM-500. Figure 3 shows the contact hot-wire device (QTM-500).

Figure 3: Contact hot-wire device (Quick Thermal Conductivity Meter: QTM-500) for measuring thermal conductivity.

A compression testing machine with a capacity of 3000 kN was used to test the concrete specimens to failure. For all specimens, the loading rate was held constant at 0.15 MPa/second. The compressive strength was recorded as a result of conducting the tests under uniform axial compression load as the crushing strength of each specimen. Compression tests were performed using the ASTM C39 Standard Test Method [21].Compression machine, 3000 kN, operated with a Cyber-Plus evolution touch-screen control unit, excellent stability, for testing cubes up to 200 mm on each side and cylinders up to 160 x 320 mm in diameter. Figure 4 shows the concrete compression machine that was used in this study.

Figure 4: Concrete compression machine, 3000 kN, for measuring compressive strength.

III. Test results and discussions

The findings of the thermal conductivity tests on concrete specimens are summarized in Table 2. Figure 5 depicts the variation in concrete thermal conductivity with aggregate size for various pozzolana substitution percentages. The test result shows that the aggregate size has no substantial influence on the thermal conductivity of concrete for different pozzolana substitution percentages. Similar results have been observed by [13]. In this study, the thermal conductivity was reduced when the percentage of pozzolana substitution increased from the control concrete (0% substitution) to 30% pozzolana substitution, independently of the pozzolana aggregate size. However, for concrete with more than 30% pozzolana substitution, the thermal conductivity increases with the increase in aggregate size. Results indicated that for concrete with a pozzolana aggregate size of 9.50 mm, the thermal conductivity decreases from 1.38 W/m.°C to 0.53 W/m.°C when the percentage of pozzolana substitution increases from 10% to 30%, as against the control value of 1.78 W/m.°C. The maximum improvement in the thermal conductivity for concrete was achieved with a pozzolana aggregate size of 9.50 mm with 30% pozzolana substitution, where the thermal conductivity decreased from 1.78 W/m.°C to 0.53 W/m.°C with a 70% reduction. Hence, concrete with 30% pozzolana substitution and a pozzolana aggregate size of 9.50 mm, having the lowest thermal conductivity value of 0.53 W/m.°C, is recommended as green concrete to improve the insulation properties of a building.

Table 2: Thermal conductivity results of concrete specimens.

Pozzolana's aggregate substitution percentage (%)	**Thermal conductivity (W/m.°C)**				
	Aggregate size (mm)				
	2.36	4.75	9.50	12.50	19.00
0	1.72	1.76	1.78	1.77	1.75
10	1.46	1.42	1.38	1.42	1.42
20	1.08	1.12	1.02	1.11	1.06
30	0.58	0.60	0.53	0.57	0.58
40	0.72	0.68	0.64	0.74	0.75

Pozzolana concrete could be used as an insulator because it is commonly used as a porous material while maintaining appropriate levels of mechanical characteristics, such as compressive strength. The addition of pozzolana aggregate to the concrete mix may have reduced thermal conductivity. This matches with the findings of [22–24], where the authors stated that thermal conductivity decreases with the addition of pozzolana materials to concrete. According to [23], the high silica content of the pozzolana contributes to the reduction in thermal conductivity. Furthermore, due to the porous nature of the pozzolana, the reduction in thermal conductivity could be caused by a decrease in the specific gravity of pozzolana concrete compared to natural concrete, resulting in a decrease in the density of pozzolana concrete and, as a result, minimizing thermal conductivity. According to several researchers, such as [19, 25], the thermal conductivity of concrete reduces as the density of the material decreases. The test results reveal that the addition of insulating materials such as pozzolana aggregate results in a reduction of water absorption in the concrete mix and, consequently, decreases the thermal conductivity of concrete.

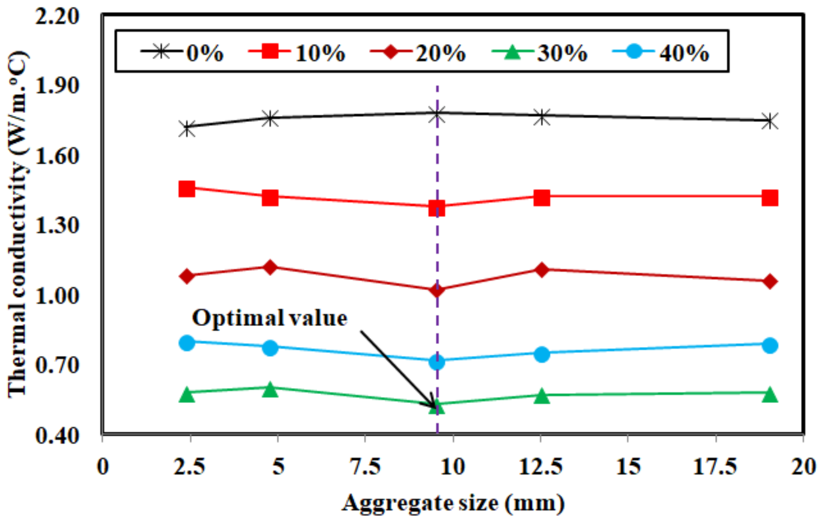

Figure 5: The variation of thermal conductivity of concrete with aggregate size for different pozzolana substitution percentages.

The findings of the compressive strength tests on concrete specimens are summarized in Table 3. Figure 6 demonstrates the variation in concrete compressive strength with aggregate size for different pozzolana substitution percentages. The test result shows that the aggregate size has a substantial influence on the compressive strength of concrete for different pozzolana substitution percentages. According to [16], both cement content and aggregate size had a significant impact on the compressive strength of brick aggregate concrete. From Figure 6, it can be observed that for concrete with pozzolana substitution less than 20%, the compressive strength of concrete increases as the aggregate size increases from 2.36 mm to 19.00 mm.

However, the compressive strength increases with the increase in aggregate size up to 9.50 mm and declines as the aggregate size grows beyond 9.50 mm for concrete with a pozzolana substitution of 20% or more. When the proportion of pozzolana substitution is increased from 10% to 30%, the compressive strength of concrete with a pozzolana aggregate size of 9.50 mm increases from 10.02 MPa to 14.56 MPa, compared to the control value of 9.10 MPa. The maximum improvement in the compressive strength for concrete was achieved with a pozzolana aggregate size of 9.5 mm with a 30% pozzolana substitution, where the compressive strength increased from 9.10 MPa to 14.56 MPa with a 60% increment. Hence, concrete with 30% pozzolana substitution and a pozzolana aggregate size of 9.50 mm having the highest compressive strength value of 14.56 MPa is recommended as the desired strength characteristic for concrete.

Table 3: Compressive strength results of concrete specimens.

Pozzolana's aggregate substitution percentage (%)	**Compressive strength (MPa)**				
	Aggregate size (mm)				
	2.36	4.75	9.50	12.50	19.00
0	5.92	7.60	9.10	10.15	11.02
10	6.34	8.84	10.02	11.23	12.15
20	7.93	10.68	12.45	11.68	11.08
30	9.12	11.45	14.56	12.25	10.60
40	8.55	11.18	14.05	12.32	10.85

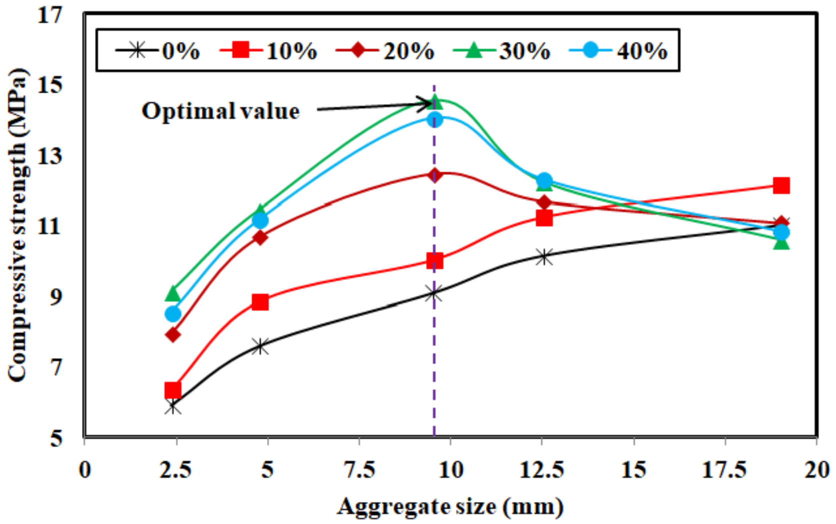

Figure 6: The variation of compressive strength of concrete with aggregate size for different pozzolana substitution percentages.

For concrete with pozzolana substitution of 20% or more, the surface area provided by the 9.50 mm aggregate size was more than that provided by the 12.50 mm aggregate size, and this is true for the aggregate size between 12.50 mm and 19.00 mm. As a result, the smaller surface area provided by larger aggregate is responsible for a lower number of bonds between gels and aggregate surfaces, which leads to lower compressive strength. The porosity of pozzolana aggregate compared to natural aggregate was the main cause of this reduction. When large-sized aggregate is utilized, the concrete may become more heterogeneous, which may inhibit the uniform distribution of load when pressured, finally leading to internal bleeding. Furthermore, due to the development of microcracks, the transition zone becomes much weaker, resulting in decreased compressive strength. Additionally, an increase in moisture content causes more space between aggregates in concrete mixtures, lowering compressive strength. This matches with the findings of [26]. The increased absorption into the pozzolana aggregate minimizes water collection in the vicinity of the aggregate in concrete with an aggregate size of between 2.36 mm and 9.50 mm. Consequently, the transition zone in the aggregates becomes much stronger and denser [27, 28]. In addition, a stronger interfacial bond between gels and aggregates is generated due to the large pozzolana reaction. This contributes to the concrete mixes' greater compressive strength.

IV. Conclusion

This experimental work focuses on the thermal conductivity and compressive strength of pozzolana concrete with a view to ascertaining its insulation and mechanical characteristics using twenty-five concrete specimens. Furthermore, the use of pozzolana aggregate as a partial substitution of natural aggregate in the concrete mix for different aggregate sizes was discussed. Based on the study performed, the findings can be summarized as follows:

1. The aggregate size has no substantial influence on the thermal conductivity of concrete for different pozzolana substitution percentages.
2. The thermal conductivity is reduced when the percentage of pozzolana substitution increases from the control concrete (0% substitution) to 30% pozzolana substitution, independently of the pozzolana aggregate size. However, for concrete with more than 30% pozzolana substitution, the thermal conductivity increases with the increase in aggregate size.
3. Concrete with 30% pozzolana substitution and a pozzolana aggregate size of 9.5 mm provides the optimal results, where the thermal conductivity decreases from 1.78 W/m.^{o}C to 0.53 W/m.^{o}C with 70% reduction, while the compressive strength increases from 9.10 MPa to 14.56 MPa with 60% increment.
4. For concrete with pozzolana substitution less than 20%, the compressive strength of concrete increases as the aggregate size increases from 2.36 mm to 19.00 mm. However, for concrete with pozzolana substitution of 20% and more, the compressive strength increases with the increase in aggregate size up to 9.50 mm and decreases as the aggregate size increases beyond 9.50 mm.
5. The use of pozzolana aggregate as a partial substitution of natural aggregate in structural materials provides the desired thermal conductivity and compressive strength as green concrete, thereby reducing the energy consumption required for cooling and heating in buildings, leading to energy conservation.

Conflict of Interests

The authors state that there are no conflicts of interest in the publishing of this paper.

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