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Effect of Ceramic Dust as Partial Replacement of Cement on Lightweight Foamed Concrete

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Abstract: Disposal of waste into the landfill causes severe impact on the environment. One of the waste products is ceramic waste. Ceramic waste has some excellent properties in its durability, hardness, and highly resistant to biological, chemical, and physical degradation forces. These excellent properties of the ceramic waste may make it suitable to be used in concrete. This study investigates the effect on the fresh properties and compressive strength of lightweight foamed concrete with different percentage of ceramic dust replacement level towards the cement and three different levels of water-cement ratio. 0%, 5%, 15%, and 25% of replacement level with 0.52, 0.56, and 0.60 water-cement ratios respectively for each replacement level was used as the parameter to investigate the fresh properties, and strength performance of lightweight foamed concrete. The stability and consistency of every mix are studied as well. From the study, it was observed that the incorporation of ceramic waste dust partially replaced the cement did not affect on the fresh properties of the foamed concrete. However, the compressive strength of foamed concrete was affected by ceramic waste dust partially replaced the cement.

Keywords: Ceramic dust, foamed concrete, performance index, compressive test

1. Introduction

Steel, concrete, wood, marble, and others are construction and building materials in the world [1]. Concrete is one of the most widely used construction materials in the construction world due to the engineering characteristics and properties of concrete. Concrete is formed by a mixture of cement, water, sand, fine, and coarse aggregate, which are the primary raw materials of the concrete. The aggregate and the mix proportion can affect the physical and chemical properties of concrete such as workability, strength, stability, and durability. Generally, concrete is strong in compression but weak in tension. Therefore, steel, timber, admixture, fibre, and others are used to enhance the concrete's performance. With the rapid growth and price increases in construction materials, some construction company has been using lightweight concrete as a building material in a structure. The density of lightweight concrete is about 800 kg/m^3 to 1850 kg/m^3. Lightweight concrete is classified into lightweight aggregate concrete, lightweight foamed concrete (LFC), and autoclaved aerated concrete (AAC). Lightweight aggregate concrete is the most popular type using in industries among lightweight concrete.

Foamed concrete (FC) is first used in the Greek construction industry in the 1980s. Its high thermal insulation and lightweight properties, combined with convenience in casting and economy in energy and time, seem to be the most outstanding advantages for the use of foamed concrete in buildings in particular for cast-in-place roofs and floors. By controlling the foam dosage added into the foamed concrete, a broad range of densities of the foamed concrete between 300 to 1800 kg/m^3 can be produced, which can be used to construct the structural building, filling grades or the thermal

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insulation wall. Compared with normal-weight concrete, foamed concrete is cheaper to produce due to its minimum aggregate consumption as the air voids are entrapped with a foaming agent [2]. Hence, foamed concrete has a very low self-weight. It can reduce the steel reinforcement required for beams, slabs, or columns in a building. Foamed concrete has a very high workability [3]-[5]. It also able to fill any shape of hollow without vibration or compaction

Nowadays, the world is facing the problem of the management of solid waste and liquid waste, which are produced by various manufacturing companies, thermal power plants, municipal solid waste, and other wastes. Disposal of waste into the land causes a severe impact on the environment. According to [6], about 54% of the construction and demolition waste is contributed by ceramic waste. About 11,166 million m^2 of the global production of the ceramic tile during the year 2011 to 2012. Ceramic products are part of the important construction materials used in buildings. Ceramic is a mixture of clay, sand and other natural materials, moulded into the desired shape and then fired at a high-temperature kiln [7]. Generally, according to [8], ceramic waste can be separated into two categories by the source of raw materials. The first category is ceramic waste generated by fired ceramic waste, which the structural ceramic factories that only use red paste for the product and the second category are ceramic waste produced in stoneware ceramic. Some sources of ceramic waste for the first category are such as bricks, blocks and roof tiles. Whereas, the sources of second category ceramic waste are wall and floor tiles, and sanitary ware. That waste tile is created in different forms, which are produced in the companies during and after the production process due to faults found in construction, human activities, and inappropriate raw materials. Ceramic waste is not recycled in any form at present. Hence, they are useless in practice and resulted in the disposal and environmental problem. Nevertheless, ceramic waste has some excellent properties in its durability, hardness, and high resistance to biological, chemical, and physical degradation forces. These excellent properties including have a lightweight of about 14 kg/m^3, stain-free, acid and alkali resistance, very long life, good thermal insulation capacity, and low water absorption. These excellent properties of ceramic waste may make it suitable to be used in concrete.

Concrete is a combination of coarse and fine aggregates, cement, and water. All the raw materials used in producing the concrete consumed natural resources and led the concrete to become the most consumed human-made material on earth. If comparing all the material that is used to produce concrete, cement can be considered as the expensive material due to manufactured by using an energy-intensive process. However, the production of cement is one of the significant producers of carbon dioxide, which contributes about 8% of global carbon dioxide emission and leading the cause of global warming [9].

In order to solve this problem, there are some research works have been carried out to determine some of the locally available materials partially or fully replace the cement. The application of ceramic dust is unusually used in the construction field due to ceramic dust as the supplementary material to replace cement material is not familiar in this society, and lack of information can be referred to. Ceramic dust can be characterised by its chemical composition that is mainly composed of silica and alumina. Both minerals represent more than 80% of the ceramic dust composition. Most of the previous researchers found to study the engineering properties of the ceramic waste partially replace the aggregate in the normal-weight concrete. [10]-[16] investigate the engineering performance such as mechanical properties, fresh properties, and microstructures test as the replacement level from 0% to 100% of total natural aggregate volume with ceramic waste in normal-weight concrete. [8;17-18] studied the strength properties, absorption effect shrinkage, freeze-thaw resistance, consistency, workability, and other more on the mortar and normal-weight concrete with cement replaced by ceramic waste. Up to date, there is a lack of information and investigation on the effect on the strength performance of the foamed concrete with partial incorporation with ceramic waste. As such, the utilisation of ceramic dust has been carried out in this study to determine the potential of it as supplementary cementitious material in terms of pozzolanic activity for foamed concrete performance.

2. Experimental Programme

This section describes the material preparation, mix proportion, casting procedures, and the method to conduct the fresh properties and compressive strength test.

2.1 Material Preparation

The raw materials used in this study include cement, fine aggregates, water, foaming agent, and ceramic dust. YTL Cement Bhd manufactured ordinary Portland cement (OPC) used in this study with the strength class of 52.5N and complies with the requirements of Type I cement stated in [19]. The sand particles were oven-dried for 24 hours with a temperature of 105 ± 5 °C and sieved through a 600 μm sieve pan. The source of water used in this study was tap water that complied with [20]. The dry pre-form foam method was adopted to produce foam using a foam generator. The foaming agent used was a synthetic based foaming agent produced by Sika Kimia Sdn. Bhd. The dilution ratio of the foaming agent to water was 1:20 in volume. The locally produced ceramic dust choose in this study with the loss of ignition about 2.3%.

2.2 Mix Proportion

In this experiment, four types of foamed concrete with a targeted density of 1200 ± 50 kg/m^3 cast. The four types of foamed concrete have different replacement levels of cement, which are 0%, 5%, 15%, and 25%. The mix proportion of base materials was calculated based on the ratio set for each base material. The cement to sand ratio is set as 1:1 for all four types of LFC. There are three sets of water-cement ratio, which is 0.52, 0.56, and 0.60 chosen for this study. The results obtained from 7 days and 28 days compressive test was used to evaluate the performance behaviour of the foamed concrete. Table 1 tabulates the mass of materials required in this study to produce 1 m3 of LFC with a density of 1200 kg/m^3. The required mass of foam, F_m calculated based on referring to the formula tabulated by [21], as shown in Eqn. (1).

$$F_m = B_m \times F_d \left(\frac{1}{T_d} - \frac{1}{B_d} \right) \quad (1)$$

where, F_m = required mass of foam, B_m = base mix mass, F_d = foam density, T_d = target density, and B_d = base density.

Table 1 - Mix proportions of foamed concrete partially replaced with ceramic dust in 1m^3

Mix	Replacement level (%)	w/c	Mass of Base Materials (kg)				
			Cement	Ceramic dust	Sand	Water	Foam required
FC-0.52-0	0	0.52	476.0	0	476	247.5	18.85
FC-0.56-0	0	0.56	469.0	0	469	262.6	18.38
FC-0.60-0	0	0.60	462.0	0	462	277.2	17.96
FC-0.52-5	5	0.52	452.2	23.8	476	247.5	18.85
FC-0.56-5	5	0.56	445.6	23.4	469	262.6	18.38
FC-0.60-5	5	0.60	438.9	23.1	462	277.2	17.96
FC-0.52-15	15	0.52	404.6	71.4	476	247.5	18.85
FC-0.56-15	15	0.56	398.7	70.3	469	262.6	18.38
FC-0.60-15	15	0.60	392.7	69.3	462	277.2	17.96
FC-0.52-25	25	0.52	357.0	119.0	476	247.5	18.85
FC-0.56-25	25	0.56	351.8	117.2	469	262.6	18.38
FC-0.60-25	25	0.60	346.5	115.5	462	277.2	17.96

2.3 Casting Procedure

The base materials for the casting of foamed concrete, such as OPC, sand, water, and ceramic dust, were weighed based on the mix proportion calculated. All the dry materials were mixed, and water was poured in progressively until a consistent concrete slurry was produced. The flow table test conducted before the addition of foam into the concrete slurry. The density of the concrete slurry was measured using a 1-litre container, and the amount of foam required was weighed, added, and mixed until a homogeneous foamed mortar with a density of 1200 ± 50 kg/m^3 is achieved. An inverted slump test was conducted after the foamed concrete was mixed to achieve the target density. The concrete slurry was poured into the moulds and left to set for 24 hours before demoulding. The hardened density of concrete specimens was measured and recorded before cured in water for 7-day and 28-day before testing.

2.4 Fresh Properties Test

During the mixing of the fresh base mix of foamed concrete, the flow table test and inverted slump test was conducted to determine the fresh properties of the concrete mix in terms of consistency and flowability. Flow table test was conducted according to [22] before the foam was added into the base mix slurry. The frustum mould was filled and with compacted fresh base mix slurry. The frustum mould was then lifted and dropped 25 times within 15 seconds. The number of drops and diameter of the spread in two perpendicular directions to each other were measured and recorded.

An inverted slump test was carried out according to [23] after the fresh foamed concrete mix achieved a density of 1200 ± 50 kg/m^3. The inverted mould was filled with the fresh foamed concrete mix without the need for compaction, and then the mould was lifted vertically at a constant speed. The largest diameter of the spread and the diameter perpendicular to it were measured. The slump flow value was calculated as the average of the two diameters.

2.5 Compressive Strength Test

The concrete compressive test was performed referring to [24]. The specimens sized 100 mm cubical was used to test for the compressive strength of foamed concrete. The compressive test was conducted using INSTRON 5582 Universal Testing Machine at a constant rate of 0.02 mm/s axial compression load until failure. An average of compressive strength was taken by testing three specimens for each type and curing age of foamed concrete.

3. Results and Discussion

This section discusses the result in detail for the fresh properties test, stability and consistency, and the effect of ceramic dust on the compressive strength of the foamed concrete.

3.1 Fresh Properties Test

Table 2 shows the results of the overall fresh properties of foamed concrete with various densities and ceramic waste replacement levels. From the results, as the water-cement ratio increased from 0.52 to 0.60, the flow table and inverted slump spread value is also increasing. This increment value of the spread value proved that as the water-cement increase, the workability increases. Besides that, the foamed concrete with ceramic waste replacement has higher flowability than the control sample, which is the ordinary foamed concrete without any cement replacement. Among all the samples, foamed concrete with a 5% replacement level have the highest flowability. The spread value behaviour also shows a similar trend with the study from [25].

To achieve the target density, the theoretical foam amount was calculated before casting. However, it was found that the actual foam required to achieve the target density of 1200 kg/m^3 ± 50 kg/m^3 during the casting is higher than the calculated theoretical required foam, as shown in Table 2. The highest percentage difference is about 89%. The high percentage of differences might due to the bursting of the foam during the foamed concrete mixing process.

Table 2 - Overall fresh properties of foamed concrete

Mix	Foam Added (g)	Foam Required (g)	Fresh Density (kg/m^3)	Consistency	Flow Table Test		Inverted Slump value (cm)
					No. of drops	Spread value (cm)	
FC-0.52-0	242	136	1185	0.988	25	23.5	43.0
FC-0.56-0	235	132	1158	0.965	17	25.0	50.0
FC-0.60-0	155	129	1225	1.021	12	25.0	50.5
FC-0.52-5	245	136	1215	1.013	23	25.0	48.5
FC-0.56-5	231	132	1156	0.963	15	25.0	53.3
FC-0.60-5	211	129	1242	1.035	9	25.0	58.3
FC-0.52-15	149	136	1211	1.009	25	24.8	45.0
FC-0.56-15	195	132	1197	0.998	19	25.0	48.7
FC-0.60-15	205	129	1170	0.975	11	25.0	52.3
FC-0.52-25	200	136	1190	0.992	25	25.0	44.5
FC-0.56-25	250	132	1177	0.981	13	25.0	58.5
FC-0.60-25	220	129	1174	0.978	11	25.0	58.0

3.2 Stability and Consistency

For foamed concrete, the stability and consistency check are essential to ensure that the bubble inside the foamed concrete does not bust during the concrete hydration process while maintaining the foamed concrete is in the target range. The consistency is considered good if the ratio of fresh density over the target density is 1. From Table 3, the result shows that all the samples are nearer to unity, and this shows that the fresh density of foamed concrete is within the allowable range of target density.

For good stability, the ratio of fresh density to hardened density has to be 1. Table 3 shows the average stability for each type of sample. The result shows that all the stability value is near to 1. The unity value indicates no or less busting of foam during the hydration process, and the hardened density is controlled within the allowable density range.

3.3 Compressive Test of Foamed Concrete

The compressive strength is affected by the concrete density. Overall, the compressive strength for 1200 kg/m^3 density of lightweight foamed concrete in this study is rather low if compare to higher densities of foamed concrete.

According to [26], it is observed that compressive strength has a direct relationship with density where a reduction in density exponentially and adversely affects the compressive strength. A study was done by [27] indicate that the compressive strength of foamed concrete is primarily a function of dry density and is little affected by the percentage of cement replaced by ash. The addition of foam created air voids and gives a lower density and adversely depleted the compressive strength. Apart from that, [28] concluded that the compressive strength decreases as the porosity increases.

Table 3 - Stability and consistency of foamed concrete

Mix	Stability	Consistency
FC-0.52-0	1.074	0.988
FC-0.56-0	1.021	0.965
FC-0.60-0	1.042	1.021
FC-0.52-5	1.097	1.013
FC-0.56-5	1.054	0.963
FC-0.60-5	1.133	1.035
FC-0.52-15	1.006	1.009
FC-0.56-15	1.016	0.998
FC-0.60-15	1.013	0.975
FC-0.52-25	1.083	0.992
FC-0.56-25	1.036	0.981
FC-0.60-25	1.006	0.978

Performance index (PI) was calculated to improve the consistency of the results obtained by considering the variation of density of LFC cast. With PI, the comparison between the compressive strength of each type of LFC is more accurate. The performance index (PI) was calculated to estimate the compressive strength of LFC per 1000 kg/m^3. The compressive strength was obtained at 7-day and 28-day for different ceramic dust replacement levels with three different water-cement (w/c) ratios. As shown in Fig. 1 to Fig. 3, it is noticed that the compressive strength of concrete was obtained at a later age. The results of 0%, 5%, 15%, and 25% replacement of ceramic dust with w/c 0.52, 0.56, and 0.60 show that the compressive strength of 7-day is lower than 28-day. From Fig. 1 to Fig. 3, the graph's behaviour of compressive strength performance index to different ceramic dust replacement levels are similar to the study from [29]. For the control mix, which is 0% replacement level, the compressive strength performance index per 1000 kg/m^3 is 1.56 MPa^3, 2.52 MPa, and 1.99 MPa for water-cement ratio 0.52, 0.56, 0.60 respectively. The results show a similar result with the study from [30], [31] at about 1200 kg/m^3 density of foamed concrete, which is below 3.5 MPa. From Fig. 1 to Fig. 3, it can also deduce that the optimum water-cement ratio for 0% replacement is 0.56, as such the compressive strength for 0% start to decrease at a water-cement ratio of 0.60.

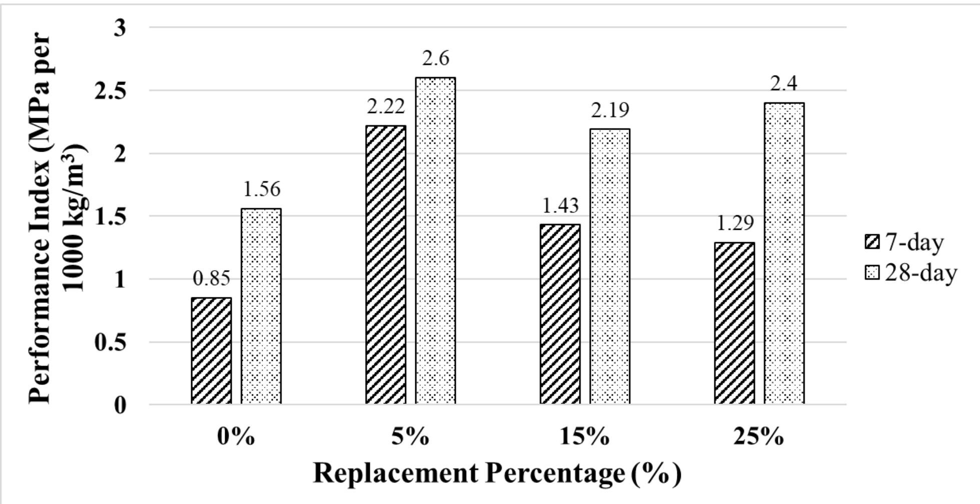

Fig. 1 - Graph of compressive strength performance index against different ceramic dust replacement level at water-cement ratio 0.52

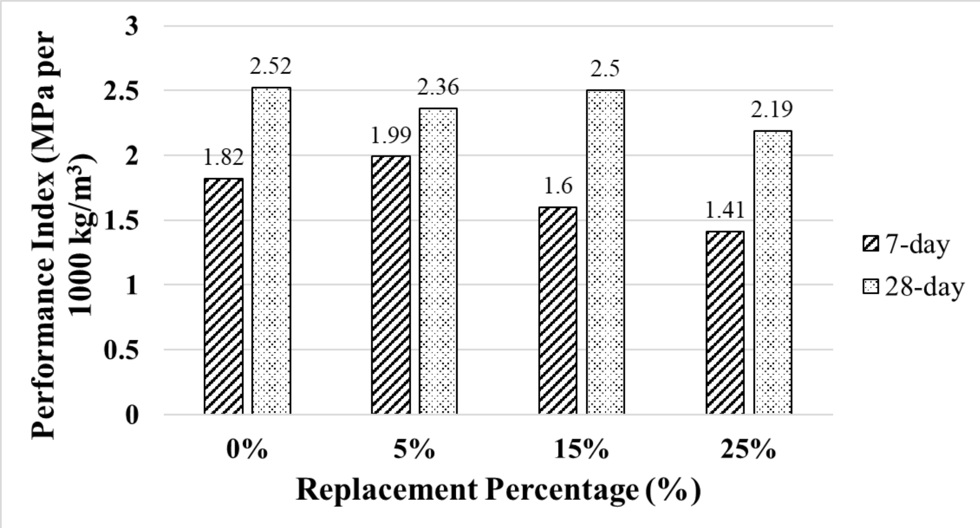

Fig. 2 - Graph of compressive strength performance index against different ceramic dust replacement level at water-cement ratio 0.56

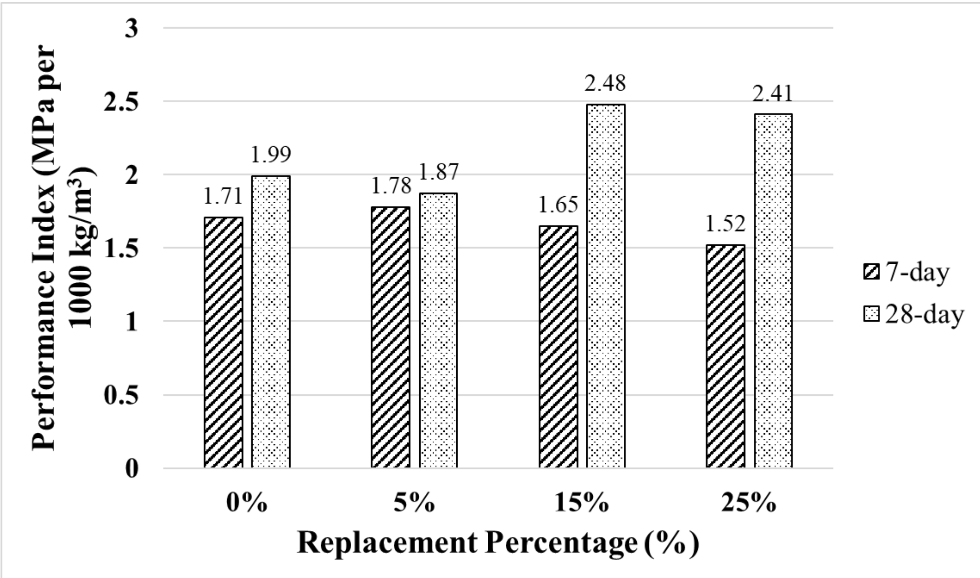

Fig. 3 - Graph of compressive strength performance index against different ceramic dust replacement level at water-cement ratio 0.60

From Fig. 1 to Fig. 3, it is noted that in the 28-day compressive strength performance index, the strength slightly decreases after ceramic dust percentage increased beyond 5% for w/c 0.52 and 15% for both w/c 0.56 and 0.60. The compressive strength reduced might due to the bleeding and segregation in the foamed concrete, which caused by excessive free water content in the mixes with ceramic waste content. It can be noticed that the ceramic dust optimum replacement level increased as the water-cement ratio increased. For w/c 0.52, the optimal compressive strength performance index per 1000 kg/m^3 is 2.6 MPa at a 5% replacement level. For w/c 0.56 and 0.60, the optimal compressive strength performance indexes per 1000 kg/m^3 are 2.5 MPa and 2.48 Mpa at a 15% replacement level. This also indicates that ceramic dust might consume more water for the hydration process as the replacement level increased. Besides that, in Fig. 1 to Fig. 3, it is also noticed that the optimum compressive strength performance index is similar to the 0% for a higher w/c ratio, which is 0.56 and 0.60. However, comparing with all the samples to the low w/c ratio such as 0.52, the compressive strength performance index increased about 67% at a 5% replacement level from 0% and obtained the highest compressive strength among the three different optimal mixtures. This is might due to the open porosity of the mixtures increased correspondingly when increasing the replacement level. As mentioned before, the porosity in lightweight foamed concrete will affect its compressive strength much. According to [32], this also indicates the possible durability problems for mixes with higher Portland cement replacement. Besides that, [33],

[34] show a similar trend of results on the compressive strength relation with open porosity percentage of mortar paste and concrete respectively, when increased the replacement level to the Portland cement.

Besides, Table 4 shows the standard deviation based on the 7-day and 28-day compressive strength performance index for each mixture. From Table 4, it can be deduced that the standard deviation is in the range of 0.016 to 0.278 MPa per 1000 kg/m^3. The low standard deviation indicates that the compressive strength tends to be close to the mean of the set data in each mixture.

Table 4 - Standard deviation for each mixture

Mix	Standard deviation based on the compressive strength performance index (MPa/1000 kg/m^3)	
	7-day	28-day
FC-0.52-0	0.257	0.122
FC-0.56-0	0.076	0.040
FC-0.60-0	0.051	0.035
FC-0.52-5	0.026	0.113
FC-0.56-5	0.038	0.062
FC-0.60-5	0.082	0.016
FC-0.52-15	0.064	0.215
FC-0.56-15	0.122	0.063
FC-0.60-15	0.129	0.148
FC-0.52-25	0.138	0.097
FC-0.56-25	0.278	0.034
FC-0.60-25	0.126	0.074

4. Conclusions

The incorporation of ceramic waste dust partially replaced the cement did not affect the fresh properties of the foamed concrete. As the water-cement ratio increased from 0.52 to 0.60, the flow table and inverted slump spread value increased. The foamed concrete with ceramic waste replacement exhibits higher flowability as compare to the control sample. Apart from that, the stability and consistency of foamed concrete, with and without partially replaced with waste ceramic dust, are near unity. Nevertheless, the compressive strength of foamed concrete affected by ceramic waste dust partially replaced the cement. For the compressive strength, a 5% replacement level with w/c of 0.52 recorded the highest strength among all the samples. For w/c 0.56 and 0.60, the ceramic dust replaced up to 15% increases the strength of foamed concrete but reduced when exceeding the optimum replacement level, which is 15%. The highest compressive strength performance index in 0.52, 0.56, and 0.60 water-cement ratios are 2.6 MPa, 2.5 MPa, and 2.48 MPa, respectively.

In the future study, more comprehensive testing such as mechanical and physical properties of the foamed concrete using ceramic dust as a partial replacement for cement can be performed to have more in-depth details on the effect of ceramic dust on the foamed concrete.

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