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MECHANICAL PROPERTIES OF FOAMED CONCRETE (FC) USING HIGH-VOLUME FLY ASH

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ABSTRACT: The production of foamed concrete (FC) using high-volume fly ash concrete (HVFAC) is an effort developed to minimize the adverse effects of construction activities on the environment. This initiative is associated with the ability of HVFAC to significantly reduce the use of Portland cement, including its lightweight nature, which requires a large volume of substitute additives. Therefore, this study aimed to evaluate the effectiveness of foam concrete produced using different HVFAC contents. The experimental process included the creation of five specimen variations. These included non-fly ash FC (FC0), which was used as the control with 100% Portland cement, and four variations, namely FC50, FC60, FC70, and FC80, produced using 50, 60, 70, and 80% fly ash of the total cementitious, respectively. Dry density and compressive strength were tested on the hard specimens at ages 7, 28, and 56 days, while the Initial Rate of Water Absorption (IRA) was conducted at the age of 56 days. The results showed that in 56 days, the increase in fly ash content in FC was inversely proportional to dry density and compressive strength values. However, the increase showed a direct proportionality to the water absorption value. FC produced with fly ash, which accounts for 50–80% of the total binder, can be efficiently used as an alternative infill wall material with substantial properties of being lightweight, cost-effective, and environmentally friendly, with acceptable technical specifications.

Keywords: Foamed concrete, High-volume fly ash, Dry density, Compressive strength, Water absorption

1. INTRODUCTION

Cement is a main ingredient in the production of concrete, accounting for approximately 10 to 15% of the total volume. However, it has some adverse effects on the environment as the manufacturing process produces 7% of global CO_2 emissions. Cement plants also generate water and cement combustion dust as byproducts in addition to the release of CO, NO_x, SO_x, and particulate matter. A previous report stated that the production of a metric ton of cement required one million MJ of energy [1-3]. The environmental impact of construction activities on the environment has led to extensive study on materials engineering. Some of the various strategies established include the introduction of supplementary cementitious and sustainable materials, waste resources, and the development of lightweight and efficient materials.

Supplementary cementitious material (SCM) was introduced to replace the volume of cement in concrete with alternative pozzolanic materials to obtain a more sustainable and environmentally friendly construction process. An example of these materials is fly ash, which is produced through burning coal to generate energy in power plants. Fly ash is a finely split amorphous aluminosilicate interacting with calcium hydroxide at room temperature to form calcium-silicate hydrate (C-S-H), a pozzolanic substance with cementitious capabilities. Furthermore, it can be combined with Portland cement as an alternative material to produce concrete. The reaction of this material with calcium hydroxide ($CaOH_2$) during the hydration of the Portland cement is used to create new cementitious components.

High-volume fly ash concrete (HVFAC) is the process of using a high percentage of fly ash as an additional cementitious ingredient in concrete mixes. According to ACI 232.2R [4], HVFAC contains more fly ash, constituting a minimum of 50% of the total mass of the cementitious components. This innovation provides a comprehensive solution to the challenges associated with meeting the increasing demand for concrete in the future and enhances the sturdiness and sustainability of concrete structures at minimal additional cost [5]. Furthermore, it presents an environmentally responsible solution for disposing of significant quantities of waste from coal-fired power plants [6, 7]. The developed HVFAC can improve concrete performance, demonstrating commendable mechanical properties, low permeability, good durability, and control of concrete temperature due to the cement hydration process [8].

In a related context, foamed concrete (FC) is an efficient building material produced by blending sand, cement, water, and foam agents. It is normally produced by mixing cement paste or mortar with separately produced and preformed foam. The ratio of foam to mortar determines the density of FC, and its properties can be enhanced using the density of sand, stone ash, or limestone. During production, air bubbles are evenly distributed throughout the mass, requiring stable foam cells during mixing, moving, pumping, and setting of fresh concrete. The size of the distinct cells or bubbles varies between 0.1 and 1 mm. Moreover, FC is free-flowing, allowing the placement without being compacted. The presence of random air content also makes the density of the mixture to be 400–1850 kg/m^3. Previous studies showed that FC was very flowable, required less cement, and made better use of aggregate [9-12].

There have been several previous studies on the utilization of high-volume fly ash for FC, using a percentage of 0–60% to explain the impact of varying the percentage of foam and fly ash on the mechanical properties of FC [13]. In another study, up to 70% fly ash was used, and it was concluded that percentages up to 55% did not significantly affect the compressive strength [14]. Kearsley *et al.* [15], using 0–75% fly ash, came to the conclusion that the compressive strength of FC correlates with its dry density.

Comprehensive testing procedures, including fresh and hardened forms, are needed to ensure the quality of concrete during production. The workability is normally determined using fresh concrete through a slump test. Meanwhile, there are two methods of analyzing the hard concrete, namely the destructive and the non-destructive tests. The destructive aspect uses Universal Testing Machine (UTM) to test several samples in the laboratory and obtain compressive strength values. Compressive strength is a mechanical property of concrete that measures the ability to resist compression or crushing and is typically evaluated in pounds per square inch (psi) or megapascals (MPa). This property is significant to the appropriateness of concrete in constructing buildings, bridges, roads, and other structures. The results obtained from the compressive strength test are used to determine the quality, optimize mixes, evaluate strength, identify defects, and measure the age of concrete. However, some situations require conducting the test directly in the field instead of the laboratory. This shows the importance of using the appropriate tool to measure the compressive strength of hard concrete quickly, practically, and non-destructively. The non-destructive method can be applied on-site (in situ), and the results are presented in the form of approximate concrete strength data [16]. Some of the methods frequently used include Hammer tests, Ultrasonic Pulse Velocity (UPV), and Initial Rate of Water Absorption (IRA).

According to ASTM C67 [17], IRA is the volume of water absorbed over one minute by a concrete or brick surface measuring 30 by 30 inches. Specifically, IRA is used to calculate water absorption rate of the concrete surface by measuring the mass gain of a sample after one of the sides absorbed water over time. During the process of hydrating and drying mortar, a chemical bond is usually formed between the mortar and the brick. The creation of this bond in the pores requires the absorption of enough water and cement from the mortar by the bricks, leaving only the quantity required for hydration in the joint. Moreover, the acceptable range for IRA is 10 to 30 grams, as the bond can be weakened when the brick is excessively dry due to the absorption of much water from the mortar, showing a significant influence on the bond [18].

Based on the previous background, this study aimed to examine the application of FC produced by partially replacing cement with different percentages of high-volume fly ash. The experiment was conducted in the laboratory using specimens produced from five variations. This included variation 1, namely non-fly ash FC (FC0), as the control with 100% Portland cement FC as well as, FC50, FC60, FC70, and FC80 produced using 50, 60, 70, and 80% fly ash of the total cementitious, respectively. Moreover, during the experimental analysis, both freshly made and hardened concrete were tested. The hard concrete tested was used to evaluate the density, compressive strength, and water absorption at the ages of 7, 28, and 56 days, respectively. Moreover, the test specimens used were 100 mm x 200 mm cylinders for density and compressive strength and 150 mm x 150 mm cubes for water absorption (IRA). The results obtained are then discussed, analyzed, and compared with previous studies to draw conclusions.

2. RESEARCH SIGNIFICANCE

The application of a high volume of fly ash in FC is an effort implemented to produce cost-effective and environmentally friendly construction materials. In previous studies, the replacement of more than 50% of cement in total cementitious with fly ash is projected to enhance the performance of FC in addition to its function as a green material. An increase of up to 80% in fly ash in this study can reduce costs with acceptable performance. Consequently, this study was conducted to analyze the performance of FC produced using different high volumes of fly ash to complement cement. The results were expected to provide additional information needed to recommend the most appropriate approach to applying fly ash as a substitute cementitious for cement in FC.

3. MATERIAL AND METHODS

3.1 Material Properties

This study used ordinary Portland cement (OPC) from 1 brand purchased from a regional cement manufacturer in South Sulawesi, Indonesia. Meanwhile, fly ash (FA) was obtained from a power plant in Jeneponto Regency, South Sulawesi, Indonesia, and categorized as an F class based on ASTM C 618-05 [19], where the amount of SiO_2, Al_2SO_3 and Fe_2O_3 more than 70%. The physical and chemical properties of fly ash and Portland cement are presented in the following Tables 1 and 2, respectively.

Table 1 Physical Characteristics of OPC and Fly Ash

Properties	OPC	Fly Ash
Fineness/Blaine meter, m^2/kg	344	-
Autoclave expansion, %	0.10	-
Compressive strength test		
- 3 days, kg/cm^2	190	-
- 7 days, kg/cm^2	267	-
- 28 days, kg/cm^2	359	-
Setting time		
- Initial setting, minute	125	-
- Final setting, minute	263	-
False setting, final penetration, %	83.58	-
Air Content, % volume	4.53	-
Specific Gravity	3.10	2.05
Sieve Analysis, pass no.200, %	-	91.0

Table 2 Chemical Characteristics of OPC and Fly Ash

Properties	OPC	Fly Ash
MgO	2.58	-
SO_3	2.10	-
CaO	-	12.72
SiO_2	-	44.56
Al_2SO_3	-	14.57
Fe_2O_3	-	11.76
$SiO_2+Al_2SO_3+Fe_2O_3$	-	70.89
Loss on ignition	3.39	0.29
Insoluble residue	0.77	
Alkalies	0.31	

Meanwhile, the physical properties of the silica sand from Pinrang Regency, South Sulawesi, Indonesia, used as the fine aggregate are presented in Table 3. The description of foam agent characteristics used in this study is shown in Table 4.

Table 3 Physical characteristics of sand

Properties	Result
Dry Density	2.60
SSD Density	2.62
Clay Content (%)	0.96
Water absorption (%)	0,88
Finest Modulus	1,30
Loose Unit Weight (kg/lt)	1.29
Solid Unit Weight (kg/lt)	1.46
Water Content (%)	3.80
Impurities of organic	No. 1

Table 4 Characteristics of foam agent

Properties	Result
Composition	Surfactant blend
Appearance	Pale yellow/clear
Density	1.03 kg/L (+25°C)
PH Value	7.0 ± 1.0
Dosage	0.3 - 1.0 % by weight of cement
Advantages	Strong foaming properties allow for the production of densities as low 500 kg/m3, less segregation and bleed, improved flowability and pumpability

3.2 Mix Design

FC mix design for each variation including FCO, FC50, FC60, FC70, and FC80 is presented in Table 5. Superplasticizer admixture was added as water reducer in all the mixtures. Superplasticizer is used to reduce water usage, enhancing homogeneity and foam stability, and enhancing bonding strength.

Table 5. FC mix design (m^3)

Material	Mixed Type				
	FC0	FC50	FC60	FC70	FC80
OPC, kg	690	345	276	207	138
FA, kg	0	345	414	483	552
Sand, kg	1440	1420	1420	1410	1410
Water, l	160	161	162	162	164
Admix., l	13.8	13.8	13.8	13.8	13.8
Mortar portion,%	53.1	53.6	53.7	53.9	54.0
Foam mix. portion,%	46.9	46.4	46.3	46.1	46.0
Foam Agent/Water ratio	0.05	0.05	0.05	0.05	0.05
Wet Density kg/m^3	1223	1222	1223	1221	1221

The mix design was based on the same target wet density of fresh concrete for all variations, ranging from 1221 to 1223 kg/m^3. Additionally, the same cementitious dosage of 690 kg was used, and the foam agent dosage was 0.5%. By determining wet density ranging from 1221 to 1223 kg/m^3, increasing the amount of fly ash in the mix design decreased the portion of mortar to the total FC mix.

3.3 FC Production Process

Figure 1 to 4 depicts the production process of FC specimens. The materials used in this study consisted of foam agent, cement, fly ash, sand, water, and superplasticizer (Fig. 1), which were first tested for material characteristics.

Fig. 1 FC materials.

The production process consisted of two simultaneous stages, namely mortar production and foam mixture production, in the following order:
(1) The foam mixture, made of foam agent and water, was produced using a foam generator machine to obtain a homogeneous foam mixture as shown in Fig. 2.
(2) A concrete mixer mixes the mortar mix, which consists of cement, fly ash, sand, water, and superplasticizer. After the mortar mixture is homogeneous and evenly distributed, the foam mixture is added and stirred again for at least 4-5 minutes until the foam concrete mixture is homogeneous and has the designed workability.

Fig. 2 Producing foam mixture.

(3) After obtaining the foam concrete mixture in accordance with what has been designed, continue testing the wet density of fresh concrete (Fig. 3).

Fig. 3 Wet density testing.

(4) The last step is to cast fresh concrete into the mold, as shown in Fig. 4.

Fig. 4 Casting fresh FC into the mold.

3.4 Slump Flow Test

Slump flow testing method of FC refers to ASTM C1611 standard. This test method includes slump flow of self-consolidated concrete determination Slump Flow Test value can be used to determine the workability condition of concrete based on the spreading ability of fresh concrete expressed by a diameter quantity representing the average diameter of the spreading circle. The equipment used for the concrete slump test included base plate, slump cone, brush, stick, mini shovel, cement scoop, and tape measure.

3.5 Dry Density Test

Dry density test was based on [20], which was used to describe the unit weight of structural lightweight concrete standards. The process included removing specimens from the curing tub, weighed in water, and providing the initial "C" to show the weight in a fully submerged condition. The cylindrical specimens were removed from water and left for 1 minute on a sieve measuring 9.5 mm or more. Water was dried using a damp cloth, the weight was measured, and provided with the initial "B" to show the weight of specimens in a saturated surface dry state. Subsequently, specimens were dried completely on the surface in a chamber with a humidity of 50% ± 5% and 21°C - 25°C to obtain a weight less than 0.5% at 28 days of age. Dry weight was calculated and recorded in kilograms with the initial "A". Meanwhile, the weight of the balanced state was determined using the following Eq. (1):

$$\mathbf{E_m = (A)/(B - C)} \quad (1)$$

A : The weight of specimens at drained condition (kg)
B : The weight of specimens under saturated surface dry (SSD) conditions (kg).
C : The weight of specimens when completely submerged in water (kg).

3.4. Compressive Strength Test

Compressive strength of the hard concrete was tested using the cylindrical specimens produced in line with ASTM C39 [21] and evaluated using Universal Testing Machine (UTM). Furthermore, the calculation of compressive strength value was carried out using Eq. (2) based on the load value recorded by the testing device.

$$F_c = P/A \quad (2)$$

F_c : Concrete compressive strength (MPa)
P : Maximum load (N)
A : Surface area of specimen (mm^2)

3.5. IRA Test

IRA test was conducted based on ASTM C67 [14]. The method required drying specimens in an oven at a temperature of 110 - 115°C for 24 hours. Specimens were removed, cooled to room temperature, and dry weight was measured as Wd, while dimensions as L and B to obtain the surface area (A) for the bricks. Specimens were submerged partially in water until the moment the entire bottom surfaces were in contact with water, which was maintained till the conclusion of the test, as shown in Figure 4. Moreover, water was added for specimens with irregular surfaces to ensure proper immersion. Specimens were soaked for 1 minute ± 0.1 seconds and weighed (Ww) removal from water.

$$\mathbf{X = 30\ W/A} \quad (3)$$

X : The weight gain adjusted to the basis of a flat surface of 30 in.2 (193.55 cm^2)
W : The actual specimen weight gain (g)
A : The surface area of the specimen (cm^2)

4. RESULTS AND DISCUSSION

4.1. Slump Flow Test Result

Slump flow test results presented in Fig. 6 and Table 5 showed that the behavior of foamed fresh concrete in all variations of mix type was as self-consolidating concrete (SCC). The results showed that the addition of fly ash percentage increased the slump flow value. Fly ash enhances the workability of the FC mixture by modifying its rheological properties, resulting in a delayed setting time and improved uniformity. This modification enhances the flowability of FC.

Fig. 5 Slump flow test

Table 6 Slump test result of FC

Mixed Type	Result (S), cm
FC0	40.0
FC50	44.0
FC60	45.5
FC70	47.0
FC80	48.0

4.2. Dry Density Test Result

The results of dry density test are shown in Fig. 7. For FCO, the average hard concrete density ranged from 1338 kg/m^3 to 1342 kg/m^3. Meanwhile, FC50, FC60, FC70, and FC80 had 1317 kg/m^3 - 1330 kg/m^3, 1307 kg/m^3 - 1332 kg/m^3, 1270 kg/m^3 - 1289 kg/m^3, and 1251 kg/m^3 - 1266 kg/m^3, respectively, as shown in Fig. 6.

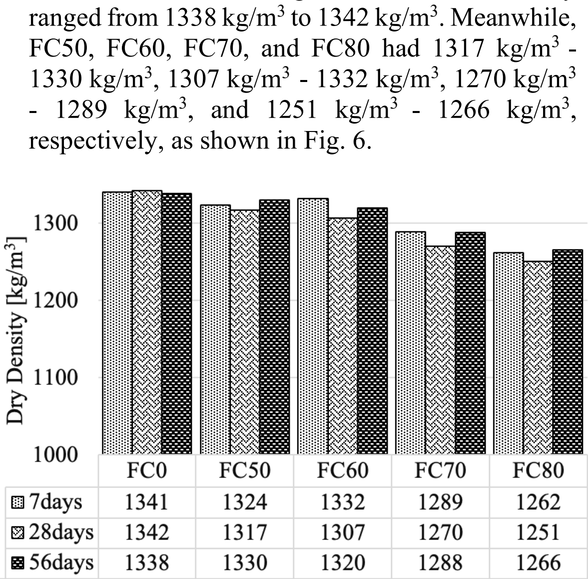
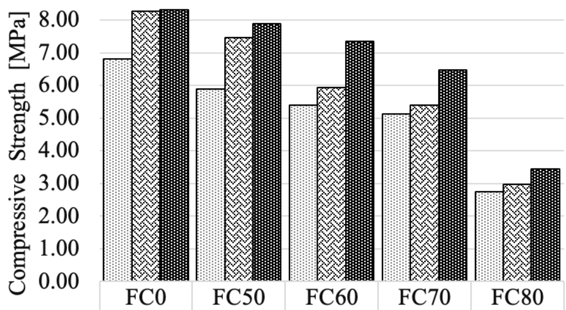


Fig. 6 Dry density test result

These results showed that dry density reduced as the content of fly ash in the mix increased. The decrease could be attributed to the increase in fly ash content, leading to a reduced portion of mortar decreases compared to the foam mixture. In addition, the density of fly ash is less than the density of cement. Consequently, after curing specimens, the resulting dry density is smaller with the increase of fly ash in the cementitious. All specimens met the specifications required for the lightweight structural concrete category, ranging from 800 kg/m^3 to 1400 kg/m^3, according to ACI 213R3 [22].

4.3. Compressive Strength Result

Compressive strength results for specimens at the age of 7, 28, and 56 days are presented in Fig. 7. Based on the results, FC0 was observed to have 6.82, 8.28, and 8.33 MPa, while FC50 had 5.90, 7.47, and 7.90 MPa. Furthermore, FC60 had 5.39, 5.94, and 7.35 MPa, FC70 achieved 5.14, 5.39, and 6.47 MPa, and FC80 had 2.76, 2.97, and 3.44 MPa. This showed that FC0 had the highest value and compressive strength diminished as the percentage of fly ash increased. The compressive strength recorded at FC0 did not increase significantly as concrete aged from 28 to 56 days, which was 0.6%. Meanwhile, there was a significant increment of 5.4, 19.1, 16.7, and 13.6% for FC50, FC60, FC70, and FC80, respectively.



	FC0	FC50	FC60	FC70	FC80
7days	6.82	5.90	5.39	5.14	2.76
28days	8.28	7.47	5.94	5.39	2.97
56days	8.33	7.90	7.35	6.47	3.44

Fig. 7 Compressive strength test result

The initial compressive strength of concrete decreases as the fly ash percentage increases, especially if the percentage is above 50%. This is due to the low reactivity of the pozzolan in the fly ash used. This difference is very significant when compared with the reactivity of OPC during the hydration process [23, 24]. The hydration reaction that occurs in OPC involves a chemical reaction between cement and water in a concrete mixture. Tricalcium silicate (C_3S) and calcium dioxide (C_2S) react with water in cement to produce calcium silica hydrate (CSH), calcium hydroxide (CH), and ettringite. This OPC hydration process tends to be rapid, giving a relatively high initial strength of concrete. While the process of hydrating in fly ash with pozzolanic materials (silicon, alumina, and iron oxides) will react with the calcium hydroxide (CH) produced during the hydration of OPC. This reaction produces additional hydrate products, such as calcium silicate hydrate (CSH), which helps improve the strength and durability of concrete. The pozzolan reaction from fly ash takes longer to peak, so the effect of increased concrete compression strength continues after the age of 28 days. More fly ash will slow down the cement hydration process, lower the hydration temperature, and reduce the compressive strength significantly [25, 26].

The results of this test are in accordance with other studies, where the increase in compressive strength of FC is influenced by dry density [27]. Generally, higher density in FC leads to greater compressive strength and lower void volume. Based on previous studies, FC is normally produced through foam and cement paste, with properties being influenced by the constituent materials. It was also observed that replacing approximately 60% of the total cementitious mass in FC with fly ash enhanced the performance of the cement paste by increasing its suitability, with a dry density of more than 1000 kg/m^3. The compressive strength of FC was found to reduce as fly ash content increased from 0-50%, followed by a significant downward trend above 55%. The percentage of cement replaced by fly ash had a significant impact on the compressive strength of FC, which was largely a function of dry density. The results showed that long-term compressive strength was not significantly influenced by the replacement of large amounts of cement with fly ash [14,15].

4.4. IRA Result

Initial Rate of Water Absorption (IRA) results for all specimens were tested at the age of 56 days, and the values were presented in Fig. 8. The results showed that FC0 had 14.547 gr/cm^2, while FC50, FC60, FC70, and FC80 produced 14.978 gr/cm^2, 15.093 gr/cm^2, 18.427 gr/cm^2, and 19.627 gr/cm^2, respectively. Because fly ash particles are smaller in size and finer in shape than cement, they can fill microscopic pores in the concrete matrix. Under these conditions, the smaller density of fly ash increases absorption, which leads to an increase in the total porosity in the FC, thus increasing water absorption.

According to ACI 228.2R-13 [28], these values met the requirement for lightweight concrete which was set below 20 gr/cm^2. The trend also showed that the addition of more fly ash increased IRA value.

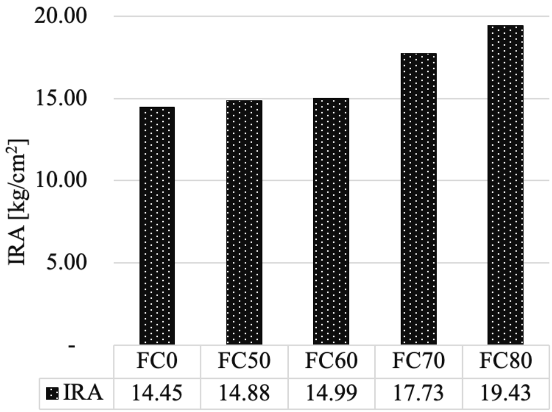


Fig. 8 IRA test value at 56 days.

The correlation between the values of dry density, compressive strength, and IRA for specimens at 56 days of age was explained in Fig. 9. The results showed that the addition of more fly ash contents to specimen led to lower dry density and compressive strength values but produced higher IRA values.

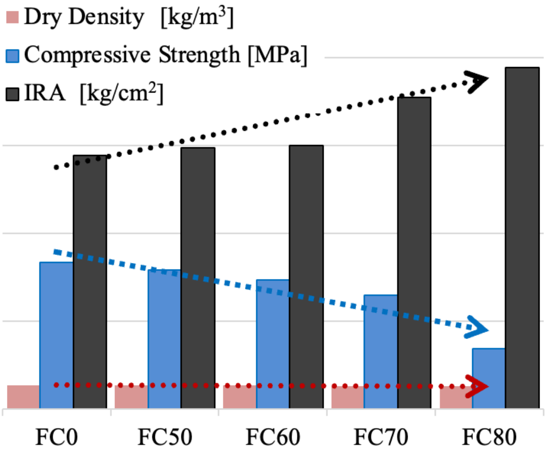


Fig. 9 Correlation between dry density, compressive strength, and IRA test value at 56 days.

6. CONCLUSIONS

Based on the results, the following conclusions were reached

1. Dry density and compressive strength of specimens decreased with increasing fly ash content at each curing age.
2. IRA value of specimens tested at the age of 56 days increased with the addition of fly ash to partially replace cement in the concrete mix.
3. The increase in fly ash content was inversely proportional to dry density and compressive strength values but showed direct proportionality to IRA value.
4. The FC test results using fly ash as a cement replacement at a percentage of 60 to 80% of the total binder resulted in acceptable performance, including specific gravity, compressive strength, and water absorption. This indicates that the foam concrete produce could be efficiently used as an alternative infill wall material with substantial properties namely lightweight, cost-effective, and environmentally sustainable, with acceptable technical specifications.

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