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MECHANICAL PROPERTIES OF HIGH-VOLUME FLY ASH CONCRETE WITH VARYING FLY ASH CONTENT

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ABSTRACT

Fly ash is widely used as a replacement for cement to produce more environmentally friendly concrete with reliable performance in construction applications. Therefore, this research aimed to analyze the mechanical properties of high-volume fly ash concrete (HVFAC) using class F fly ash with different percentages. Performance tests that were carried out included workability, unit weight, and compressive strength. Laboratory experiments were conducted by making 5 variations of mix design, namely variation 1 (FA0), which consisted of normal concrete with a control test material of 100% Portland cement. The other 4 variations were HVFAC (FA70, FA80, FA90, and FA100), which were made with fly ash content comprising 70%, 80%, 90%, and 100% of the total binders/cementitious. Fresh concrete was tested for workability, while hardened concrete was tested for unit weight and compressive strength at ages 3, 7, and 28 days on test specimens subjected to water immersion curing. The results showed that all workability of HVFAC test specimens met the self-consolidated concrete (SCC) category. The dry unit weight of all specimens met the requirements for normal-weight concrete. The results of the compressive strength test at 28 days showed that the addition of fly ash percentage caused a decrease in the compressive strength value of the entire HVFAC, but still exceeded the minimum requirements for high-quality concrete. HVFAC with variations FA70, FA80, and FA90 met the requirements of ASTM C618-12a based on the evaluation of Strength Activity Index (SAI) values at 7 and 28 days of age, while FA100 did not meet the requirements.

Keywords: high volume fly ash, chemical admixture, unit weight, compressive strength, SAI.

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1. INTRODUCTION

Cement is an essential component of concrete, serving as the main binding medium between coarse and fine aggregate through a hydration process to form a strong paste. To produce cement, a large amount of energy is required, causing side effects that can impact the environment. Burning fossil fuels such as coal and natural gas to heat furnaces to temperatures of around 1450°C requires a large amount of energy, leading to greenhouse gas emissions. Furthermore, cement manufacturing, particularly the limestone calcination process, produces a significant amount of CO_2 which contributes to climate change. The manufacturing process produces CO_2 amounting to approximately 7% of the total greenhouse gas emissions that occur on Earth [1, 2, 3]. The growth of cement factories throughout the world poses a threat to human survival when there is a lack of anticipation and control efforts. To address this challenge, the optimal effort is to reduce the use of cement and replace it with another material such as fly ash, which can function as a binder/cementitious. This material should be more environmentally friendly to minimize negative impacts on the environment [3].

Fly ash is a by-product of burning coal in steam power plants, which is often been used as a partial replacement for cement in making concrete, offering several benefits both from a technical and environmental perspective. ASTM C618-12 divides fly ash into two main groups, namely class F and class C, which are based on the source and properties [4, 5]. Class F originates from burning anthracite or bituminous coal with a calcium oxide (CaO) content of less than 20% and a total amount of silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3) of more than 70%. This class of FA reacts with calcium hydroxide ($Ca(OH)_2$) and water to form cementitious compounds, but do not possess the properties independently. It is commonly used to increase the strength and durability of concrete, suitable for structures that require resistance to chemical attack, such as sulfate/seawater, and can reduce the heat of hydration in massive concrete. Meanwhile, class C is sourced from lignite or sub-bituminous coal with a CaO content of more than 20% calcium oxide (CaO) and a total amount of silica (SiO_2), alumina (Al_2O_3), and ferric oxide (Fe_2O_3) above 50%. Specifically, class C has pozzolanic and cementitious properties, showing the ability to react with ($Ca(OH)_2$) and harden when exposed to water. It is often used for concrete mixtures that require high initial strength and fast setting time, indicating its suitability for use in road infrastructure and rigid pavement projects [2, 6]

Previous research shows that the use of class F fly ash as a partial replacement of cementitious in concrete has a good impact on concrete performance. In the compressive strength test, samples using class F showed lower initial compressive strength values compared to the control. Due to the pozzolan reaction, the compressive strength increased gradually over a longer period, while there was no significant improvement in test specimens without fly ash after the age above 56 days. The compressive strength of concrete using class F is influenced by the chemical composition, physical properties, and the amount of fly ash content, as well as the curing time of the test specimens [6, 7].

The use of fly ash as cement replacement for 10% to 30% of the cement material is a common practice. However, with the recent development, the target value for replacement has been increased to above 50% in concrete. According to ACI 232.2R, this type of concrete is categorized as High-Volume Fly Ash Concrete (HVFAC). Research has shown that high levels of fly ash can increase the workability, strength, and durability of concrete. As replacement material, the use of 100% fly ash combined with an alkali activator can replace the role of cement in concrete or mortar. Previous research shows that class F fly ash can be used as a 100% replacement material for cement due to its high silicate (Si) and aluminate (Al) content [8,9]. The use of fly ash in HVFAC offers numerous benefits, which include responding to the increasing need for concrete in the future, the capacity of concrete structures, and their sustainability at lower costs. Furthermore, the application is an appropriate alternative for the use of waste originating from coal-fired power plants which often cause environmental problems [10, 11, 12].

Concrete mix performance can be enhanced to meet construction requirements by incorporating chemical admixtures. These admixtures are commonly used to adjust the quality and characteristics of fresh concrete, ensuring its quality during mixing, delivery, pouring, and curing processes. They address potential issues that may arise during construction and reduce production costs. According to ASTM C494, chemical admixtures for concrete are classified into seven categories, each with specific functions and characteristics. For example, Type E admixtures are designed to reduce and accelerate water absorption.

Based on the description, this research aimed to analyze the mechanical properties of HVFAC using class F with different percentages. Experiments were carried out in the laboratory by making 5 variations of mix design, namely variation 1 (FA0), comprising normal concrete with 100% Portland cement as a control test object. The other 4 variations of HVFAC were FA70, FA80, FA90, and FA100, each was made using FA content of 70, 80, 90, and 100% of the total cement. The performance tests carried out were the workability, unit weight, and compressive strength. Fresh concrete was tested to determine workability, while hardened concrete was examined by testing cylindrical specimens with a diameter of 150 mm and a length of 300 mm. Additionally, density and compressive strength tests at the ages of 3, 7, and 28 days were carried out on specimens subjected to the preservation process using the curing method of immersion in water.

2. MATERIAL AND METHOD

The research method used was based on the sequence as shown in the flow chart in Figure-1.

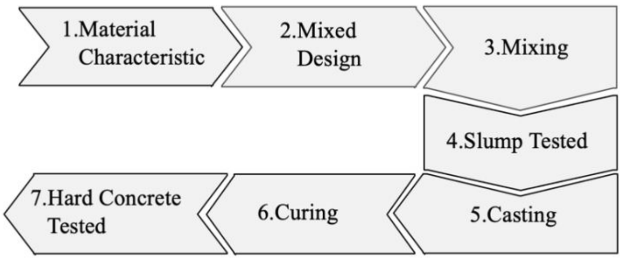

Figure-1. Research flowchart.

2.1 Cementitious Properties

This research used Ordinary Portland Cement (OPC) and fly ash as cementitious materials. At the beginning of the research process, testing of the characteristics of cementitious was carried out before being used for the concrete mixture by determining the physical and chemical properties of OPC and fly ash. These characteristic values determine the mix design plan that would be made. The results presented in Table 1 showed that OPC used met the requirements of ASTM C150. Portland cement with these specifications has been used in previous research on high-strength concrete (HSC), and high-volume fly ash concrete (HVFAC) with good test results and according to standards [10, 13]. The characteristics of fly ash originating from waste from the power plant in Jeneponto, South Sulawesi, Indonesia, obtained a specific gravity value of 2.08. The results of the sieve inspection showed that the percentage of fly ash that passed sieve no. 200 was 91.5%. By visual observation, it appears that the OPC used is gray, while the fly ash used is brown to gray.

Table-1. Physical Characteristic OPC and fly ash.

Properties	OPC	Fly Ash
Autoclave expansion, %	0.11	-
Fineness, m^2/kg	348	-
Time of setting, minute a. Initial Set b. Final Set	 125 261	 - -
Compressive strength, kg/cm^2 a. 3 days b. 7 days c. 28 days	 191 265 369	 - - -
False set, final penetration, %	83.61	-
Air Content, % volume	4.49	-
Specific Gravity	3.17	2.08
Sieve Analysis	-	91.5% pass no. 200

Table-2 shows the results of tests carried out on the chemical characteristics of OPC and fly ash. Based on the data, fly ash has a combined chemical composition of SiO_2, Al_2SO_3, and Fe_2O_3 of 70.95% and a CaO content of 12.69%. These results showed that fly ash used in this research was categorized as class F. This is by the requirements of ASTM C618-1 and confirmed in previous research results [10, 14].

Table-2. Chemical characteristic OPC and fly ash.

Properties	OPC	Fly Ash
MgO	2.68	-
SO_3	2.13	-
SiO_2	-	44.60
Al_2SO_3	-	14.65
Fe_2O_3	-	11.7
CaO	-	12.69
Loss on ignition	3.38	0.29
Insoluble residue	0.77	
Alkalies	0.29	

2.2 Aggregate Properties

The aggregate used was based on the availability of local materials around Makassar City, South Sulawesi Indonesia. In this research, the aggregate used consisted of coarse aggregate (crushed stone) with a size of 10/20 mm and fine aggregate (sand). Specifically, the coarse aggregate was sourced from the production of a stone crushing machine using Bili-bili river material, Gowa Regency, South Sulawesi, Indonesia. Based on the test results shown in Table 3, the aggregate physical properties met ASTM C33 specifications. Additionally, river sand samples originating from Bili-bili, South Sulawesi, met the requirements for use according to ASTM C33.

Table-3. Physical characteristics of aggregate.

Properties	Coarse Agg	Fine Agg
Fineness Modulus	6.90	3.00
Colloid Content, %	0.75	4.72
Water absorption, %	1.36	2.79
Specific Gravity	2.60	2.57

2.3 HVFAC Mix Design

This mix design uses ACI standards with a target compressive strength of Fc 35 MPa for control specimen design. The design consists of 5 variations, namely variation 1 (FA0), comprising normal concrete with a test material of 100% Portland cement. Other 4 variations of HVFAC, included FA70, FA80, FA90, and FA100, each of which was made with a certain amount of fly ash, consisting of 70, 80, 90, and 100% total cementitious.

2.4 Concrete Testing

Concrete testing that was carried out in this research included tests on fresh and hardened concrete. Slump tests were carried out on fresh concrete to assess workability, according to procedures based on ASTM C1611, followed by casting cylindrical test specimens measuring 150 mm x 300 mm (shown in Figure-1). Making and Curing Concrete Test Specimens in the Field followed the standards in ASTM C31 as a reference in this study.

Figure-2. (a) Slump test (b) Specimens casting.

Testing of hardened concrete was carried out at ages 3, 7, and 28 days using cylindrical specimens that had been cured by immersion in water according to ASTM C31. The curing method of concrete by immersion in water is shown in Figure-3. Testing of hardened concrete with compressive strength of cylindrical test specimens was determined using the ASTM C39 procedure, including preparation and testing stages.

Figure-3. Water submerged curing.

2.5 Strength Activity Index (SAI)

Strength Activity Index (SAI) is a measure used to assess the quality of pozzolan or fly ash materials applied as cement replacement. In this research, the SAI test was carried out to determine the effect of the additional materials on the compressive strength of mortar or concrete mix. ASTM C311 provides procedures for testing pozzolan or fly ash, including methods for determining SAI, such as preparation material, mortar mix proportion, mixing the mortar, casting in mold, curing of specimens, compressive strength testing, and calculating

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the SAI. SAI is expressed as a percentage of the compressive strength of the test mix to the compressive strength of the control mix, as expressed in the formula below.

$$SAI = \frac{Fc,specimen}{Fc,control} x\ 100\% \quad (1)$$

Fc specimen is the average strength of the specimen
Fc control is the average strength of the control specimen

ASTM C311 requires a minimum SAI value of 75% at 7 or 28 days for pozzolan or fly ash to be considered eligible.

3. RESULTS AND DISCUSSIONS

3.1 HVFAC Mixed Design Result

The mixed design of concrete mix used by prioritizing the availability of materials around the research location is explained in Table-4:

Table-4. HVFAC mix design.

Code	Material [kg]					
	OPC	Fly Ash	Coarse Agg.	Fine Agg.	Admix	Water
FA0	526	0	760	870	7.80	115
FA70	158	368	760	870	7.80	120
FA80	105	421	760	870	7.80	120
FA90	53	473	760	870	7.80	120
FA100	0	526	760	870	7.80	120

3.2 Fresh Concrete Behavior

The slump flow test on the control specimen (F0) obtained an average value of 702 mm. For all HVFAC variations, including FA70, FA80, FA90, and FA100, the average slump flow value is 724-754 mm, as shown in Table 5. This shows that according to the ACI 237R-07 standard, all mix variants are categorized as Self Consolidated Concrete (SCC) [15]. Based on visual observation, all fresh concrete mixes are adhesive and cannot be separated. This is in line with Malhotra and Mehta's statement [12, 16], where the use of fly ash with a content of more than 50% of the total weight of cementitious only increases maximum strength, durability, and concrete workability. HVFAC mixes are generally very cohesive, showing minimum or no bleeding and segregation, with excellent workability. Protection against water loss is essential to prevent plastic shrinkage cracking.

Table-5. Slump test result.

Code	Slump [mm]		
	min	max	average
F0	696	708	702
F70	718	730	724
F80	730	742	736
F90	742	758	750
F100	750	758	754

3.3 Hard Concrete Behaviour

Hard concrete test results were assessed by measuring the unit weight and compressive strength at the ages of 3, 7, and 28 days. Figure-4 shows the variations in dry unit weight of concrete with varying percentages of FA in three test periods, namely 3, 7, and 28 days. Based on FA0 data (without FA), an increase was observed in dry unit weight from 2397 kg/cm³ to 2402 kg/cm³, and 2423 kg/cm³ on days 3, 7, and 28, respectively. Concrete with FA70 also showed an increase in dry unit weight from 2420 kg/cm³ to 2442 kg/cm³, and 2458 kg/cm³. Furthermore, FA80 had a dry unit weight of 2428 kg/cm³, increasing to 2442 kg/cm³, and 2471 kg/cm³. For FA90, dry unit weight increased from 2433 kg/cm³ to 2454 kg/cm³, and 2473 kg/cm³. Concrete with FA100 showed an increasing trend in dry unit weight from 2433 kg/cm³ on day 3, to 2455 kg/cm³ on day 7, and 2475 kg/cm³ on day 28.

The results showed that increasing the percentage of fly ash in concrete mix consistently led to higher unit weight over time, with a significant rise at each test period (3, 7, and 28 days). Concrete with a higher percentage of FA70 to FA100 had a greater dry unit weight compared to FA0. The most significant increase in unit weight from day 7 to 28 occurred in FA80, FA90, and FA100 mixes, showing optimal strength development. Therefore, the use of FA as a partial replacement for cement in the concrete mix can increase the density and potential strength of the material, serving as a good alternative in high-performance concrete construction.

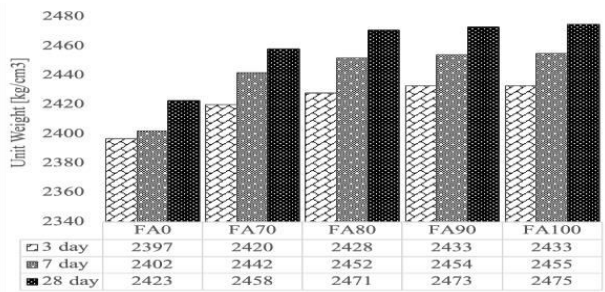

Figure-4. Unit weight test results.

Figure-5 shows the variations in compressive strength of concrete with various percentages of FA at 3, 7, and 28 days. For FA0, the compressive strength increased from 18.6 MPa to 24.0 MPa, and 42.6 MPa, on days 3, 7, and 28, respectively. FA70 showed an increase in compressive strength from 17.7 MPa to 23.2 MPa and 41.2 MPa, according to the testing periods. Furthermore, FA80 had a compressive strength of 15.2 MPa on day 3, which increased to 22.8 MPa on day 7, and 39.6 MPa on day 28. For FA90, there was a corresponding increase in compressive strength from 12.3 MPa to 19.8 MPa and 37.8 MPa in all testing periods. FA100 also showed an increase from 6.8 MPa to 8.5 MPa and 23.1 MPa, respectively.

Based on Figure-5, it was discovered that increasing the percentage of fly ash in concrete mix tended to reduce the initial compressive strength (3 days) but gradually increased over 28 days. Specifically, FA0 had the highest compressive strength in each test period, followed by FA70, FA80, FA90, and FA100. This showed that full fly ash replacement did not provide optimal results in terms of initial compressive strength at 28 days. A significant increase in compressive strength from day 7 to day 28 was observed in all variations. This showed that the use of fly ash required a longer time to achieve maximum compressive strength. Although fly ash could be used as a partial replacement for cement in the concrete mix, the optimal percentage required consideration to achieve a balance between initial and long-term compressive strength. Additionally, the use of class F in HVFAC with a percentage of 50% - 90% would reduce compressive strength as fly ash content increased [17].

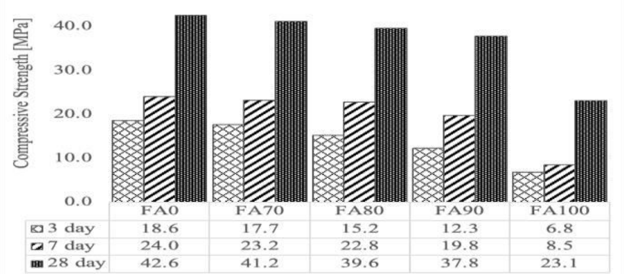

Figure-5. Compressive strength results.

3.4 Strength Activity Index (SAI)

SAI of fly ash was calculated by directly comparing the compressive strength of concrete with varying fly ash contents at 70%, 80%, 90%, and 100% with the control specimen. This method was used to assess the effectiveness of fly ash as a cement replacement material in determining the optimal percentage that could be used to achieve the desired concrete performance [18, 19].

Table-6. Strength Activity Index (SAI) results.

Code	SAI [%]		
	3 day	**7 day**	**28 day**
F0	-	-	-
F70	95.1	96.6	96.8
F80	81.9	94.8	93.0
F90	66.0	82.3	88.8
F100	36.5	35.5	54.2

Table-6 shows SAI values for concrete with varying percentages of FA70, FA80, FA90, and FA100 at all ages At 7 and 28 days of age, FA70 produced SAI values of 96.6% and 96.8%, FA80 had 94.8% and 93.0%, FA90 showed 82.3% and 88.8%, while FA100 had the lowest at 35.5% and 54.2%. This shows that as the level of fly ash as a cement substitute increases the SAI value decreases. Based on the evaluation of SAI values aged 7 and 28 days, there was a strong reaction from the C-S-H gel composition in fly ash. Therefore, only variations FA70, FA80, and FA90 met the SAI criteria according to ASTM C618-12a where the SAI value at 7 or 28 days was greater than 75%. Whereas in FA100 the value achieved is below 75% so it does not meet the requirements.

4. CONCLUSIONS

In conclusion, this research showed that the dry unit weight of all HVFAC test specimens met the requirements for normal-weight concrete according to ASTM C138. The compressive strength value of all specimens was lower compared to FA0. The increase in the percentage of fly ash as cement replacement was inversely proportional to the resulting compressive strength value. The use of class F fly ash with the addition of chemical additives produced HVFAC with high workability, showing characteristics as Self Compacting Concrete. Based on the SAI value at 28 days, HVFAC FA70, FA80, and FA90 met the requirements of the ASTM C618-12a standard. This showed that fly ash used in the research could be applied in a variety of mixes with fly ash contents of 70%, 80%, and 90%. Meanwhile, the use of 100% fly ash as cement replacement did not meet standard requirements.

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