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UTILIZATION OF HIGH-VOLUME FLY ASH AS A SUPPLEMENTARY CEMENTITIOUS MATERIAL IN ENVIRONMENTALLY FRIENDLY CONCRETE

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ABSTRACT

Innovations in material technology are expected to reduce the use of commercial cement and replace it with other environmentally friendly materials with the same performance as normal concrete. **Aim:** This study aim to analyze the mechanical property of High-Volume Fly Ash Concrete (HVFAC) using F class fly ash with different mix percentages. **Methodology and Results:** The experiment was conducted in laboratory scale. Four variations of test specimens consisted of: 1 variation (F0), which is conventional concrete with 100% Portland cement as control specimen, and three variations of HVFC (F70, F80, and F90), which were made with fly ash content (%) 70, 80, and 90 of total cementitious. Fresh concrete testing to determine workability, while hard concrete testing is done by density and compressive strength tests at the age of 3, 7, and 28 days on specimens that have been treated with the water submerged curing method. **Conclusion, significance, and impact of study:** All HVFAC specimens fulfill the Self Compacting Concrete (SCC) category. The compressive strength test results at 28 days showed that the addition of fly ash percentage caused a decrease in compressive strength values in all HVFAC variants, but still exceeded the minimum requirements of high and medium quality concrete. All HVFAC variations meet the requirements of ASTM C618-23 based on the evaluation of Strength Activity Index (SAI) values at 7 and 28 days of age. The utilization of 90% fly ash as a cement substitute resulted in an environmentally friendly concrete product based on the concept of cleaner production.

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1. INTRODUCTION

Today, concrete is a widely used construction material in the rapidly growing infrastructure development. Conventional concrete requires a large amount of raw materials, including aggregates and water, which can put pressure on local natural resources and potentially cause environmental degradation. In addition, one of the main natural materials required is Portland cement, as the main binder in concrete manufacturing. However, a new problem arises because Portland cement is a major contributor to greenhouse gas emissions. The cement industry is one of the largest sources of CO_2 emissions in the world. The Portland cement production process is estimated to contribute 6 to 7% of the total CO_2 gas to the earth's atmosphere each year (Deja *et al.,* 2010; Sunarno *et al*., 2023a). The production of cement for concrete produces high CO_2 emissions, which contribute to climate change. Thus, it is necessary to make massive efforts to anticipate environmental crises due to this activity and aim towards achieving sustainable development goals. One such effort is to reduce the use of Portland cement by replacing most of its volume with other materials that are environmentally friendly but with comparable performance; in our case, by utilizing fly ash, which is waste from the production process of electrical energy.

Fly ash is a waste generated in coal combustion during the energy production process in coal-fired power plants. Most of the current global electricity demand, particularly in many Asian countries, is supplied by coal-fired power plants. As a result, in recent decades, an increasing amount of fly ash and bottom ash have been generated as by-products of this type of power plant worldwide. Of this enormous amount of fly ash and bottom ash, only about 70%, 60%, and 50% are reused in China, India, and the United States, respectively (Yao *et al.,* 2013). A large amount of the remaining fly ash is disposed of in landfills, ash ponds, or mine pits with potential risks of air and groundwater pollution as well as serious accidents (Fernández-Jiménez *et al.,* 2015; Rashad 2015; Tang *et al*., 2016). Indonesia potentially encounters these fly ash waste problems. As a country with the largest source of coal in Southeast Asia, in 2019, Indonesia contributed about 88% of coal to Southeast Asian countries, where the majority was used as an energy source (Triani *et al.*, 2023).

Fly ash contains several toxic elements, including Chromium (Cr), Nickel (Ni), Zinc (Zn), Arsenic (As), Selenium (Se), Cadmium (Cd), Antimony (Sb), Mercury (Hg), and Lead (Pb) in the

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same concentration as the source coal. Conventional management of fly ash as waste, as is commonly practiced today, poses a significant storage problem and, therefore, has the potential to pollute the environment. If used for beneficial purposes, such as in construction (cement, concrete, bricks, roads), agriculture, and hazardous waste immobilization, fly ash is categorized as non-hazardous waste (Dermatas & Meng 2003). Using fly ash as a cement replacement material is among the solutions for effective waste management in coal-fired power plants, in addition to reducing the use of cement. This is a clear example of applying the 3Rs (Reuse, Reduce, and Recycle) concept, where industries strive to reduce environmental impacts through reduced use of raw materials, reutilization of waste, and recycling of materials. Thus, besides aiming to mitigate adverse environmental impacts, initiatives such as these can provide economic benefits and enhance sustainability in the construction industry.

According to ASTM C618-12a, fly ash is divided into three categories: class N, class F, and class C. Class N and class F have a minimum combined content of SiO_2, Al_2 SO_3, and Fe_2O_3 compounds of 70%, while class C is between 50% and 70%. Other chemical requirements mentioned in the specification are a maximum of 5% sulfur trioxide (SO_3) content, a maximum of 3% free moisture, and a maximum of 5% loss of ignition.

The mass percentage of fly ash used as cement replacement in concrete varies depending on the quality of the fly ash and the mix design. The use of fly ash in high volumes has begun to be applied to producing concrete, called High Volume Fly Ash Concrete (HVFAC). ACI 232.2R defines HVFAC as concrete that contains fly ash of at least 50% of the total mass of its binder (cementitious) in the concrete mix. The high fly ash content can improve the workability, mechanical strength, and durability of the concrete. The utilization of fly ash in HVFC can provide benefits such as addressing the growing demand for concrete in the future, increasing the capacity of concrete structures and their sustainability at a lower cost, and reducing the transportation cost of sending fly ash waste to landfills, since the material is instead reused for the fabrication of new environmentally friendly concrete. In addition, the application of HVFAC is a proper alternative for using waste derived from coal-fired power plants that often cause environmental problems (Sivasundram & Malhotra, 2004). The utilization of fly ash as a cement replacement in the production of HVFAC is an example of the implementation of cleaner production principles that aim to render industrial processes more environmentally friendly

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while maintaining or even improving the quality of the concrete.

Using more than 50% fly ash as a substitute for cement in concrete mixtures causes a smaller initial compressive strength than concrete mixtures without fly ash. Still, at an age above 28 days, the compressive strength is higher and continues to increase due to the pozzolanic nature of the fly ash material, which has long-term mechanical strength. However, the application of HVFAC has several drawbacks that must be anticipated, such as slow setting time and early strength, unsuitability for cold weather, low heat of hydration, and low resistance to salt scale and carbonation (Vaishnavi & Rao 2014; Madhavi *et al*., 2014). HVFAC can be effectively used for concrete requirements in construction, provided that the resulting early-age compressive strength is acceptable for field construction and the concrete treatment is carried out in accordance with technical requirements.

Concrete admixtures play an essential role in improving the performance of concrete. It can change the properties/characteristics of fresh concrete, ensure the quality of concrete during mixing, delivery, casting, and curing, and solve the crisis that may occur during the construction process while reducing production costs. According to the ASTM C494 standard, seven types of chemical admixtures are commonly used for concrete, each with its function and characteristics. An example is the E-type chemical admixture, which functions to reduce and accelerate the absorption of water. Adding this admixture can improve the deficiencies in HVFAC in achieving the desired initial setting (Sunarno *et al.*, 2023b).

After casting, curing concrete is a very important stage. Curing ensures that the hydration reaction of cementitious compounds, including additives or substitutes, runs smoothly and avoids excessive shrinkage, which can lead to too rapid or non-uniform moisture loss that causes cracking or crazing. The usual simple curing methods are room-temperature air curing and Water-Submerged Curing (WSC).

The purpose of this study was to evaluate the performance of concrete using fly ash waste with the addition of E-type chemical admixture with the brand Nexfast, each with a variation in the percentage of fly ash mass of 70%, 80%, and 90% of the total mass of the binder. Workability testing was carried out on fresh concrete. In contrast, dry density and compressive strength were tested on hard concrete at 3, 7, and 28 days in cylindrical specimens measuring 100 mm x 200 mm using the Water Submerged Curing (WSC) method.

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2. RESEARCH METHODOLOGY

Research was conducted by experiments in the laboratory according to the flow chart in Figure 1, where the stages were: testing of material characteristics (cement, fly ash, aggregates, and admixtures), producing concrete mixes with predetermined mix designs, namely: F0, F70, F80 and F90 with fresh concrete testing, molding of specimens, curing of specimens, and testing of hard concrete (dry density and compressive strength test).

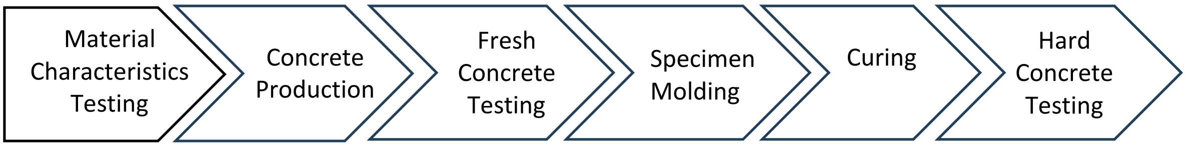

Figure 1 Research process

2.1 Material Characteristics

2.1.1 Binders Properties

The binders used in this study were Ordinary Portland Cement (OPC) cement and fly ash. The binder characteristics test was carried out by testing the physical and chemical characteristics of the binder used. The physical properties were studied through physical testing, used as the basis for concrete mix design. Chemical characteristics testing was carried out using XRF (X-ray fluorescence) testing to evaluate the chemical composition of Portland cement and fly ash. Table 1 and 2 show the results of the physical testing of Portland cement and fly ash and the testing of their chemical characteristics, respectively. Based on Table 1, show that the Portland cement used meets ASTM C150 specifications. Portland cement with these specifications has been used in previous studies with good test results and up to standards (Sunarno *et al*., 2022).

The physical examination of fly ash originating from power plant waste in Punagaya Village, Bangkala District, Jeneponto Regency, South Sulawesi, showed a specific gravity value of 2.10. The sieve examination showed that 91.0% of fly ash passed sieve no. 200. Table 2 shows the chemical composition of fly ash, with a $SiO_2 + Al_2SO_3 + Fe_2O_3$ content of 70.96%. It is concluded that the fly ash used is included in the class F category.

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Table 1 Physical characteristic of OPC and fly ash

Properties	OPC	Fly Ash
Autoclave expansion (%)	0.11	-
Fineness (m /kg^2)	350	-
Time of setting, minute		
a. Initial Set	124	-
b. Final Set	258	-
Compressive strength (kg/cm^2)		
a. three days	189	-
b. Seven days	262	-
c. 28 days	370	-
False set, final penetration (%)	83.56	-
Air Content (% volume)	4.50	-
Specific Gravity	3.16	2.10
Sieve Analysis	-	91.0% pass no. 200

Table 2 Chemical characteristics of OPC and fly ash type F

Properties	OPC	Fly Ash
MgO	2.68	-
SO_3	2.13	-
SiO_2	-	44.60
Al_2SO_3	-	14.65
Fe_2O_3	-	11.70
CaO	-	12.69
Loss on ignition	3.38	0.29
Insoluble residue	0.77	
Alkalies	0.29	

2.1.2 Aggregate Properties

The aggregate used in this study consists of coarse (crushed stone) and fine aggregates (sand). The coarse aggregate used is 10/20 mm crushed stone sourced from a stone crusher that uses raw rock materials from the Bili-bili River, Gowa Regency, South Sulawesi. The physical characteristics of the coarse and fine aggregates are shown in Table 3. The physical characteristics of the coarse aggregate meet ASTM C33 specifications. Table 3 shows that the Silica Sand used is from the Bili-bili River in South Sulawesi, and its physical characteristics meet the ASTM C33 specification.

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Table 3 Physical characteristics of aggregate

Properties	Coarse Agg 10/20	Fine Agg
Fineness Modulus	6.89	3.02
Colloid Content (%)	0.76	4.70
Moisture Content (%)	0.9	4.10
Water absorption (%)	1.35	2.85
Specific Gravity	2.60	2.56

2.2 Mix Design

The concrete mix design consisted of four variations of binder (Portland cement and *fly ash*) mixed with coarse aggregate, fine aggregate, E-type chemical admixture, and water. Variation 1 (F0) used 100% Portland cement without fly ash as the control specimen, while variation 2 (F70), variation 3 (F80), and variation 4 (F90) used fly ash 70%, 80% and 90% of the total binder mass, respectively.

2.3 Concrete Testing

Concrete tests were conducted on fresh and hardened concrete. To test the workability of fresh concrete, the slump test was carried out in accordance with ASTM C1611 standard, as shown in Figure 2. Meanwhile, the hard concrete test was carried out at the age of 3, 7 and 28 days using 100 mm x 200 mm cylindrical specimens that had been treated with the Water Submerged Curing (WSC) method according to the ASTM C31 standard. Concrete treatment with the curing method is shown in Figure 3.

Figure 2 Slump Flow Test

Figure 3 Water submerged curing

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2.4 Strength Activity Index (SAI)

ASTM C311 defines the Strength Activity Index (SAI) as the difference between the average compressive strength of reference cement (OPC) mortar at a design age and the compressive strength of mortar using substitute materials that are 20% by mass of binder. The SAI was obtained by measuring the compressive strength of mortar cubes having binders made of cement and fly ash (Patil *et al*., 2021). The test results are compared with the control mortar, a 100% cement specimen, at 3, 7, and 28 days after curing by immersing the specimen in water. Calculation of SAI values used Equation (1) as per ASTM C311.

$$SAI = \frac{A}{B}\ x\ 100 \tag{1}$$

A is the average strength of blended cement

B is the average strength of the control specimen

3. RESULTS AND DISCUSSION

3.1 HVFAC Mix Design

Table 4 shows the material composition of the mix design used in this study. Substituting cement with fly ash by 372 kg, 426 kg, and 480 kg is an effort to reduce the use of new cement, which is very energy-intensive and produces significant CO_2 emissions in the production process. Thus, the use of energy in concrete production can be minimized in accordance with the principle of cleaner production.

Table 4 HVFAC mix design

Material	F0	F70	F80	F90
Cement (kg)	532	160	106	53
Fly ash (kg)	-	372	426	480
Coarse Agg (kg)	750	750	750	750
Fine Agg (kg)	870	870	870	870
Admix (l)	7.98	7.98	7.98	7.98
Water (kg)	107	107	109	110

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3.2 Fresh Concrete Behavior

Based on the slump flow test conducted on the standard concrete mix (F0), the average slump flow of 702 mm was obtained, while in VHFAC, F70, F80, and F90 obtained higher average slump values, namely 724 - 750 mm according to Table 5.

Table 5 Slump test result

Specimens	Slump (mm)		
	max	min	average
F0	706	698	702
F70	730	718	724
F80	742	730	736
F90	758	742	750

This indicates that the mix variations behave as Self Compacting Concrete (SCC) as per ACI 237R-07. From the visual observation, we observed that the fresh concrete mix of each mix design was adhesive in nature and no segregation and bleeding occurred. The addition of fly ash in the mix increases the workability of fresh concrete, facilitating the casting process, thereby reducing the use of energy and the cost of construction implementation in the field.

3.3 Hard Concrete Behavior

The results of tests carried out on hard concrete in the form of dry density and compressive strength of concrete at 3, 7, and 28 days (Figure 4) showed that the dry density of hard concrete at the age of 28 days for each specimen using 100% cement (F0) averaged 2452 kg/m^3 and for specimens using 70% fly ash (F70) averaged 2465 kg/m^3. Meanwhile, the dry density of specimens using fly ash 80% (F80) averaged 2478 kg/m^3, and those using fly ash 90% (F90) averaged 2480 kg/m^3. Based on the volume weight, as per ASTM C138, all variations of specimens qualify as normal-weight concrete.

Figure 5 shows the comparison between the increase in curing age and the dry density of concrete from each mix design and it can be concluded that the longer the age of the concrete, the higher the dry density of the concrete occurs at the age of 3 days to 28 days. With the physical characteristics of fly ash, which is smaller in size than cement, the substitution of cement with fly ash in concrete increases its density (packing density), so that the concrete is more waterproof and resistant to sulfates and cracking while also increasing its durability

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(Madhavi *et al.*, 2014; Nath & Sarker, 2011; Vaishnavi & Rao, 2014). The service life of concrete structures is longer, which is also an aspect of cleaner production.

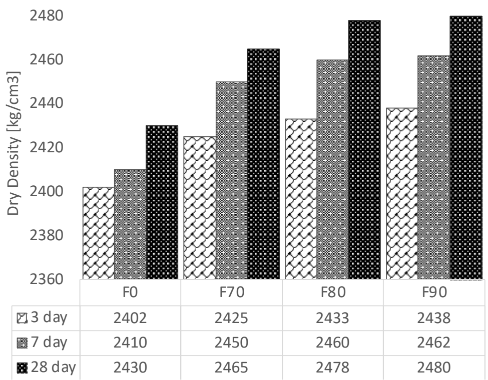

Figure 4 Dry density test results

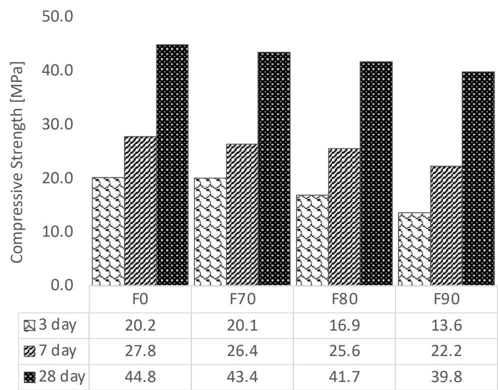

Figure 5 Compressive strength results

The results of the 28-day hard concrete compressive strength test on the test specimens using 100% cement (F0) averaged 44.8 MPa, and the hard concrete compressive strength of the test specimens using 70% fly ash (F70) averaged 43.4 MPa. Meanwhile, the compressive strength of hard concrete specimens using 80% fly ash (F80) averaged 41.7 MPa, and the compressive strength of hard concrete specimens using 90% fly ash (F90) averaged 39.8 MPa. Figure 5 shows that the compressive strength of the specimens with 100% cement content has the highest value, and with increasing fly ash content, the compressive strength results obtained will decrease. An increase in the amount of cement substitution with fly ash does reduce the compressive strength of concrete up to 28 days when compared to F0 as the control specimen, but F70 and F80 still meet the requirements as high-strength concrete, and F90 meets the requirements as medium strength concrete (based on ACI 363R-92).

The results of several previous studies (Sun *et al*., 2019; Saha, 2018) showed that the HVFAC produced an initial compressive strength lower than normal concrete without fly ash (control concrete). However, after 28 days, the strong HVFAC compressive strength developed faster. And HVFAC with 40% FA replacement at the age of 180 days is already comparable to control concrete. This is due to the reactivity of pozzolan in fly ash, which works slower than the reaction that occurs in the OPC at the time of the hydration process. The pozzolan reaction from fly ash takes longer to peak, so the effect of increased concrete compression strength

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continues after the age of 28 days. Increasing the use of fly ash will slow down the cement hydration process, reduce the hydration temperature, and reduce compressive strength significantly (Akmalaiuly *et al.,* 2023; Patil *et al.,* 2021).

3.4 Strength Activity Index (SAI) Results

Based on Table 6, it shows that the SAI values at the age of 3, 7 and 28 days for the F70 specimen are 0.96, 0.97, and 0.97, while the SAI values at the age of 3, 7 and 28 days for the F80 specimen are 0.84, 0.92, and 0.93 and the SAI values at the age of 3, 7 and 28 days for the F90 specimen are 0.67, 0.80, and 0.89. The SAI value decreased as the fly ash content increased.

Table 6 Strength Activity Index (SAI) Results

Specimens	SAI		
	Three days	Seven days	28 days
F0	-	-	-
F70	0.96	0.95	0.97
F80	0.84	0.92	0.93
F90	0.67	0.80	0.89

The SAI values at the age of 7 and 28 days (Table 6) demonstrate that there is a strong reaction of the C-S-H gel arrangement in fly ash, so that all specimen variations meet the requirements according to ASTM C618-12a, where the Strength Activity Index (SAI) value for fly ash and natural pozzolan must be > 0.75 (75%) at the age of 7 or 28 days.

3. CONCLUSION

Based on the results that the addition of fly ash increases the workability of the concrete mixture seen in the slump test. Dry density in all HVFAC specimens meets the requirements as regular weight concrete, while adding fly ash increases the density value and durability. The compressive strength of F70 and F80 meets the requirements of high-strength concrete, and F90 is medium-strength concrete. Based on the Strength Activity Index (SAI) values evaluation at 28 days, all HVFAC variations meet the requirements according to ASTM C618-12a. The utilization of fly ash as a 70% to 80% cement substitute in this study produces environmentally friendly concrete products, in line with the principles of cleaner production.

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UTILIZATION OF HIGH-VOLUME FLY ASH AS A SUPPLEMENTARY CEMENTITIOUS MATERIAL IN ENVIRONMENTALLY FRIENDLY CONCRETE

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ABSTRACT

Innovations in material technology are expected to reduce the use of commercial cement and replace it with other environmentally friendly materials with the same performance as normal concrete. **Aim:** This study aim to analyze the mechanical property of High-Volume Fly Ash Concrete (HVFAC) using F class fly ash with different mix percentages. **Methodology and Results:** The experiment was conducted in laboratory scale. Four variations of test specimens consisted of: 1 variation (F0), which is conventional concrete with 100% Portland cement as control specimen, and three variations of HVFC (F70, F80, and F90), which were made with fly ash content (%) 70, 80, and 90 of total cementitious. Fresh concrete testing to determine workability, while hard concrete testing is done by density and compressive strength tests at the age of 3, 7, and 28 days on specimens that have been treated with the water submerged curing method. **Conclusion, significance, and impact of study:** All HVFAC specimens fulfill the Self Compacting Concrete (SCC) category. The compressive strength test results at 28 days showed that the addition of fly ash percentage caused a decrease in compressive strength values in all HVFAC variants, but still exceeded the minimum requirements of high and medium quality concrete. All HVFAC variations meet the requirements of ASTM C618-23 based on the evaluation of Strength Activity Index (SAI) values at 7 and 28 days of age. The utilization of 90% fly ash as a cement substitute resulted in an environmentally friendly concrete product based on the concept of cleaner production.

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- Cleaner production
- Fly ash
- HVFAC
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- Strength Activity Index

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1. INTRODUCTION

Today, concrete is a widely used construction material in the rapidly growing infrastructure development. Conventional concrete requires a large amount of raw materials, including aggregates and water, which can put pressure on local natural resources and potentially cause environmental degradation. In addition, one of the main natural materials required is Portland cement, as the main binder in concrete manufacturing. However, a new problem arises because Portland cement is a major contributor to greenhouse gas emissions. The cement industry is one of the largest sources of CO_2 emissions in the world. The Portland cement production process is estimated to contribute 6 to 7% of the total CO_2 gas to the earth's atmosphere each year (Deja *et al.,* 2010; Sunarno *et al*., 2023a). The production of cement for concrete produces high CO_2 emissions, which contribute to climate change. Thus, it is necessary to make massive efforts to anticipate environmental crises due to this activity and aim towards achieving sustainable development goals. One such effort is to reduce the use of Portland cement by replacing most of its volume with other materials that are environmentally friendly but with comparable performance; in our case, by utilizing fly ash, which is waste from the production process of electrical energy.

Fly ash is a waste generated in coal combustion during the energy production process in coal-fired power plants. Most of the current global electricity demand, particularly in many Asian countries, is supplied by coal-fired power plants. As a result, in recent decades, an increasing amount of fly ash and bottom ash have been generated as by-products of this type of power plant worldwide. Of this enormous amount of fly ash and bottom ash, only about 70%, 60%, and 50% are reused in China, India, and the United States, respectively (Yao *et al.,* 2013). A large amount of the remaining fly ash is disposed of in landfills, ash ponds, or mine pits with potential risks of air and groundwater pollution as well as serious accidents (Fernández-Jiménez *et al.,* 2015; Rashad 2015; Tang *et al.,* 2016). Indonesia potentially encounters these fly ash waste problems. As a country with the largest source of coal in Southeast Asia, in 2019, Indonesia contributed about 88% of coal to Southeast Asian countries, where the majority was used as an energy source (Triani *et al*., 2023).

Fly ash contains several toxic elements, including Chromium (Cr), Nickel (Ni), Zinc (Zn), Arsenic (As), Selenium (Se), Cadmium (Cd), Antimony (Sb), Mercury (Hg), and Lead (Pb) in the

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same concentration as the source coal. Conventional management of fly ash as waste, as is commonly practiced today, poses a significant storage problem and, therefore, has the potential to pollute the environment. If used for beneficial purposes, such as in construction (cement, concrete, bricks, roads), agriculture, and hazardous waste immobilization, fly ash is categorized as non-hazardous waste (Dermatas & Meng 2003). Using fly ash as a cement replacement material is among the solutions for effective waste management in coal-fired power plants, in addition to reducing the use of cement. This is a clear example of applying the 3Rs (Reuse, Reduce, and Recycle) concept, where industries strive to reduce environmental impacts through reduced use of raw materials, reutilization of waste, and recycling of materials. Thus, besides aiming to mitigate adverse environmental impacts, initiatives such as these can provide economic benefits and enhance sustainability in the construction industry.

According to ASTM C618-12a, fly ash is divided into three categories: class N, class F, and class C. Class N and class F have a minimum combined content of SiO_2, Al_2 SO_3, and Fe_2O_3 compounds of 70%, while class C is between 50% and 70%. Other chemical requirements mentioned in the specification are a maximum of 5% sulfur trioxide (SO_3) content, a maximum of 3% free moisture, and a maximum of 5% loss of ignition.

The mass percentage of fly ash used as cement replacement in concrete varies depending on the quality of the fly ash and the mix design. The use of fly ash in high volumes has begun to be applied to producing concrete, called High Volume Fly Ash Concrete (HVFAC). ACI 232.2R defines HVFAC as concrete that contains fly ash of at least 50% of the total mass of its binder (cementitious) in the concrete mix. The high fly ash content can improve the workability, mechanical strength, and durability of the concrete. The utilization of fly ash in HVFC can provide benefits such as addressing the growing demand for concrete in the future, increasing the capacity of concrete structures and their sustainability at a lower cost, and reducing the transportation cost of sending fly ash waste to landfills, since the material is instead reused for the fabrication of new environmentally friendly concrete. In addition, the application of HVFAC is a proper alternative for using waste derived from coal-fired power plants that often cause environmental problems (Sivasundram & Malhotra, 2004). The utilization of fly ash as a cement replacement in the production of HVFAC is an example of the implementation of cleaner production principles that aim to render industrial processes more environmentally friendly

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while maintaining or even improving the quality of the concrete.

Using more than 50% fly ash as a substitute for cement in concrete mixtures causes a smaller initial compressive strength than concrete mixtures without fly ash. Still, at an age above 28 days, the compressive strength is higher and continues to increase due to the pozzolanic nature of the fly ash material, which has long-term mechanical strength. However, the application of HVFAC has several drawbacks that must be anticipated, such as slow setting time and early strength, unsuitability for cold weather, low heat of hydration, and low resistance to salt scale and carbonation (Vaishnavi & Rao 2014; Madhavi *et al.*, 2014). HVFAC can be effectively used for concrete requirements in construction, provided that the resulting early-age compressive strength is acceptable for field construction and the concrete treatment is carried out in accordance with technical requirements.

Concrete admixtures play an essential role in improving the performance of concrete. It can change the properties/characteristics of fresh concrete, ensure the quality of concrete during mixing, delivery, casting, and curing, and solve the crisis that may occur during the construction process while reducing production costs. According to the ASTM C494 standard, seven types of chemical admixtures are commonly used for concrete, each with its function and characteristics. An example is the E-type chemical admixture, which functions to reduce and accelerate the absorption of water. Adding this admixture can improve the deficiencies in HVFAC in achieving the desired initial setting (Sunarno *et al.*, 2023b).

After casting, curing concrete is a very important stage. Curing ensures that the hydration reaction of cementitious compounds, including additives or substitutes, runs smoothly and avoids excessive shrinkage, which can lead to too rapid or non-uniform moisture loss that causes cracking or crazing. The usual simple curing methods are room-temperature air curing and Water-Submerged Curing (WSC).

The purpose of this study was to evaluate the performance of concrete using fly ash waste with the addition of E-type chemical admixture with the brand Nexfast, each with a variation in the percentage of fly ash mass of 70%, 80%, and 90% of the total mass of the binder. Workability testing was carried out on fresh concrete. In contrast, dry density and compressive strength were tested on hard concrete at 3, 7, and 28 days in cylindrical specimens measuring 100 mm x 200 mm using the Water Submerged Curing (WSC) method.

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2. RESEARCH METHODOLOGY

Research was conducted by experiments in the laboratory according to the flow chart in Figure 1, where the stages were: testing of material characteristics (cement, fly ash, aggregates, and admixtures), producing concrete mixes with predetermined mix designs, namely: F0, F70, F80 and F90 with fresh concrete testing, molding of specimens, curing of specimens, and testing of hard concrete (dry density and compressive strength test).

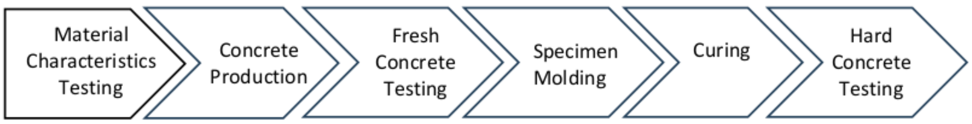

Figure 1 Research process

2.1 Material Characteristics

2.1.1 Binders Properties

The binders used in this study were Ordinary Portland Cement (OPC) cement and fly ash. The binder characteristics test was carried out by testing the physical and chemical characteristics of the binder used. The physical properties were studied through physical testing, used as the basis for concrete mix design. Chemical characteristics testing was carried out using XRF (X-ray fluorescence) testing to evaluate the chemical composition of Portland cement and fly ash. Table 1 and 2 show the results of the physical testing of Portland cement and fly ash and the testing of their chemical characteristics, respectively. Based on Table 1, show that the Portland cement used meets ASTM C150 specifications. Portland cement with these specifications has been used in previous studies with good test results and up to standards (Sunarno *et al*., 2022).

The physical examination of fly ash originating from power plant waste in Punagaya Village, Bangkala District, Jeneponto Regency, South Sulawesi, showed a specific gravity value of 2.10. The sieve examination showed that 91.0% of fly ash passed sieve no. 200. Table 2 shows the chemical composition of fly ash, with a $SiO_2 + Al_2SO_3 + Fe_2O_3$ content of 70.96%. It is concluded that the fly ash used is included in the class F category.

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Table 1 Physical characteristic of OPC and fly ash

Properties	OPC	Fly Ash
Autoclave expansion (%)	0.11	-
Fineness (m^2/kg)	350	-
Time of setting, minute		
a. Initial Set	124	-
b. Final Set	258	-
Compressive strength (kg/cm^2)		
a. three days	189	-
b. Seven days	262	-
c. 28 days	370	-
False set, final penetration (%)	83.56	-
Air Content (% volume)	4.50	-
Specific Gravity	3.16	2.10
Sieve Analysis	-	91.0% pass no. 200

Table 2 Chemical characteristics of OPC and fly ash type F

Properties	OPC	Fly Ash
MgO	2.68	-
SO_3	2.13	-
SiO_2	-	44.60
Al_2SO_3	-	14.65
Fe_2O_3	-	11.70
CaO	-	12.69
Loss on ignition	3.38	0.29
Insoluble residue	0.77	
Alkalies	0.29	

2.1.2 Aggregate Properties

The aggregate used in this study consists of coarse (crushed stone) and fine aggregates (sand). The coarse aggregate used is 10/20 mm crushed stone sourced from a stone crusher that uses raw rock materials from the Bili-bili River, Gowa Regency, South Sulawesi. The physical characteristics of the coarse and fine aggregates are shown in Table 3. The physical characteristics of the coarse aggregate meet ASTM C33 specifications. Table 3 shows that the Silica Sand used is from the Bili-bili River in South Sulawesi, and its physical characteristics meet the ASTM C33 specification.

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Table 3 Physical characteristics of aggregate

Properties	Coarse Agg 10/20	Fine Agg
Fineness Modulus	6.89	3.02
Colloid Content (%)	0.76	4.70
Moisture Content (%)	0.9	4.10
Water absorption (%)	1.35	2.85
Specific Gravity	2.60	2.56

2.2 Mix Design

The concrete mix design consisted of four variations of binder (Portland cement and *fly ash*) mixed with coarse aggregate, fine aggregate, E-type chemical admixture, and water. Variation 1 (F0) used 100% Portland cement without fly ash as the control specimen, while variation 2 (F70), variation 3 (F80), and variation 4 (F90) used fly ash 70%, 80% and 90% of the total binder mass, respectively.

2.3 Concrete Testing

Concrete tests were conducted on fresh and hardened concrete. To test the workability of fresh concrete, the slump test was carried out in accordance with ASTM C1611 standard, as shown in Figure 2. Meanwhile, the hard concrete test was carried out at the age of 3, 7 and 28 days using 100 mm x 200 mm cylindrical specimens that had been treated with the Water Submerged Curing (WSC) method according to the ASTM C31 standard. Concrete treatment with the curing method is shown in Figure 3.

Figure 2 Slump Flow Test

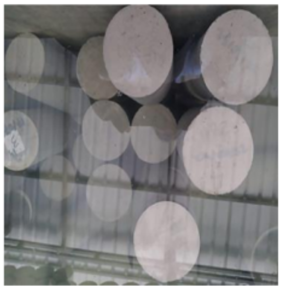

Figure 3 Water submerged curing

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2.4 Strength Activity Index (SAI)

ASTM C311 defines the Strength Activity Index (SAI) as the difference between the average compressive strength of reference cement (OPC) mortar at a design age and the compressive strength of mortar using substitute materials that are 20% by mass of binder. The SAI was obtained by measuring the compressive strength of mortar cubes having binders made of cement and fly ash (Patil *et al.*, 2021). The test results are compared with the control mortar, a 100% cement specimen, at 3, 7, and 28 days after curing by immersing the specimen in water. Calculation of SAI values used Equation (1) as per ASTM C311.

$$SAI = \frac{A}{B} \, x \, 100 \qquad (1)$$

A is the average strength of blended cement

B is the average strength of the control specimen

3. RESULTS AND DISCUSSION

3.1 HVFAC Mix Design

Table 4 shows the material composition of the mix design used in this study. Substituting cement with fly ash by 372 kg, 426 kg, and 480 kg is an effort to reduce the use of new cement, which is very energy-intensive and produces significant CO_2 emissions in the production process. Thus, the use of energy in concrete production can be minimized in accordance with the principle of cleaner production.

Table 4 HVFAC mix design

Material	F0	F70	F80	F90
Cement (kg)	532	160	106	53
Fly ash (kg)	-	372	426	480
Coarse Agg (kg)	750	750	750	750
Fine Agg (kg)	870	870	870	870
Admix (l)	7.98	7.98	7.98	7.98
Water (kg)	107	107	109	110

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3.2 Fresh Concrete Behavior

Based on the slump flow test conducted on the standard concrete mix (F0), the average slump flow of 702 mm was obtained, while in VHFAC, F70, F80, and F90 obtained higher average slump values, namely 724 - 750 mm according to Table 5.

Table 5 Slump test result

Specimens	Slump (mm)		
	max	min	average
F0	706	698	702
F70	730	718	724
F80	742	730	736
F90	758	742	750

This indicates that the mix variations behave as Self Compacting Concrete (SCC) as per ACI 237R-07. From the visual observation, we observed that the fresh concrete mix of each mix design was adhesive in nature and no segregation and bleeding occurred. The addition of fly ash in the mix increases the workability of fresh concrete, facilitating the casting process, thereby reducing the use of energy and the cost of construction implementation in the field.

3.3 Hard Concrete Behavior

The results of tests carried out on hard concrete in the form of dry density and compressive strength of concrete at 3, 7, and 28 days (Figure 4) showed that the dry density of hard concrete at the age of 28 days for each specimen using 100% cement (F0) averaged 2452 kg/m^3 and for specimens using 70% fly ash (F70) averaged 2465 kg/m^3. Meanwhile, the dry density of specimens using fly ash 80% (F80) averaged 2478 kg/m^3, and those using fly ash 90% (F90) averaged 2480 kg/m^3. Based on the volume weight, as per ASTM C138, all variations of specimens qualify as normal-weight concrete.

Figure 5 shows the comparison between the increase in curing age and the dry density of concrete from each mix design and it can be concluded that the longer the age of the concrete, the higher the dry density of the concrete occurs at the age of 3 days to 28 days. With the physical characteristics of fly ash, which is smaller in size than cement, the substitution of cement with fly ash in concrete increases its density (packing density), so that the concrete is more waterproof and resistant to sulfates and cracking while also increasing its durability

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(Madhavi *et al.*, 2014; Nath & Sarker, 2011; Vaishnavi & Rao, 2014). The service life of concrete structures is longer, which is also an aspect of cleaner production.

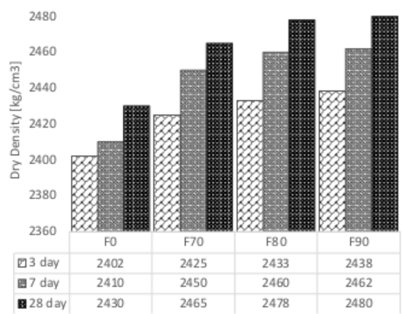

Figure 4 Dry density test results

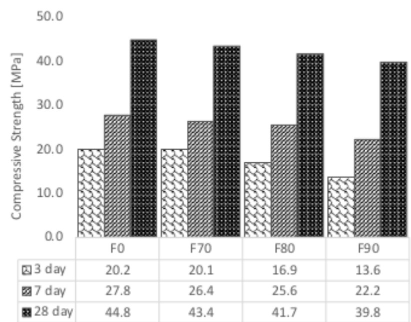

Figure 5 Compressive strength results

The results of the 28-day hard concrete compressive strength test on the test specimens using 100% cement (F0) averaged 44.8 MPa, and the hard concrete compressive strength of the test specimens using 70% fly ash (F70) averaged 43.4 MPa. Meanwhile, the compressive strength of hard concrete specimens using 80% fly ash (F80) averaged 41.7 MPa, and the compressive strength of hard concrete specimens using 90% fly ash (F90) averaged 39.8 MPa. Figure 5 shows that the compressive strength of the specimens with 100% cement content has the highest value, and with increasing fly ash content, the compressive strength results obtained will decrease. An increase in the amount of cement substitution with fly ash does reduce the compressive strength of concrete up to 28 days when compared to F0 as the control specimen, but F70 and F80 still meet the requirements as high-strength concrete, and F90 meets the requirements as medium strength concrete (based on ACI 363R-92).

The results of several previous studies (Sun *et al.*, 2019; Saha, 2018) showed that the HVFAC produced an initial compressive strength lower than normal concrete without fly ash (control concrete). However, after 28 days, the strong HVFAC compressive strength developed faster. And HVFAC with 40% FA replacement at the age of 180 days is already comparable to control concrete. This is due to the reactivity of pozzolan in fly ash, which works slower than the reaction that occurs in the OPC at the time of the hydration process. The pozzolan reaction from fly ash takes longer to peak, so the effect of increased concrete compression strength

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continues after the age of 28 days. Increasing the use of fly ash will slow down the cement hydration process, reduce the hydration temperature, and reduce compressive strength significantly (Akmalaiuly *et al.,* 2023; Patil *et al.,* 2021).

3.4 Strength Activity Index (SAI) Results

Based on Table 6, it shows that the SAI values at the age of 3, 7 and 28 days for the F70 specimen are 0.96, 0.97, and 0.97, while the SAI values at the age of 3, 7 and 28 days for the F80 specimen are 0.84, 0.92, and 0.93 and the SAI values at the age of 3, 7 and 28 days for the F90 specimen are 0.67, 0.80, and 0.89. The SAI value decreased as the fly ash content increased.

Table 6 Strength Activity Index (SAI) Results

Specimens	SAI		
	Three days	Seven days	28 days
F0	-	-	-
F70	0.96	0.95	0.97
F80	0.84	0.92	0.93
F90	0.67	0.80	0.89

The SAI values at the age of 7 and 28 days (Table 6) demonstrate that there is a strong reaction of the C-S-H gel arrangement in fly ash, so that all specimen variations meet the requirements according to ASTM C618-12a, where the Strength Activity Index (SAI) value for fly ash and natural pozzolan must be > 0.75 (75%) at the age of 7 or 28 days.

3. CONCLUSION

Based on the results that the addition of fly ash increases the workability of the concrete mixture seen in the slump test. Dry density in all HVFAC specimens meets the requirements as regular weight concrete, while adding fly ash increases the density value and durability. The compressive strength of F70 and F80 meets the requirements of high-strength concrete, and F90 is medium-strength concrete. Based on the Strength Activity Index (SAI) values evaluation at 28 days, all HVFAC variations meet the requirements according to ASTM C618-12a. The utilization of fly ash as a 70% to 80% cement substitute in this study produces environmentally friendly concrete products, in line with the principles of cleaner production.

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