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A Comparative Analysis of Superplasticizer Effects on the Flowability and Early Strength Development in Fly Ash Based Ultra High-Performance Concrete

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Abstract

This study investigates the effects of different superplasticizer compositions on the performance of ultra high-performance concrete (UHPC). Superplasticizers enhance concrete's flow and reduce air content. This study compares two types of superplasticizers naphthalene (SNF) and polycarboxylate (PCE) at 1%, 1.5%, and 2% compositions. The research method involves material testing to determine the material characteristics and mix design, then explains the mixing, curing, and testing of various UHPC mixtures with various superplasticizers and compositions. Testing was conducted to evaluate the flowability and compressive strength at 1, 3, and 7 days. Results showed that PCE at 1.5% provided the best flowability (200 mm) and early strength (71.1 MPa at 7 days), whereas SNF yielded lower flowability (110 mm) and strength (39 MPa). The superior performance of PCE is attributed to its ability to disperse cement particles and accelerate hydration. The study concludes that the superplasticizer type and composition significantly impact UHPC's flowability and early strength.

1. Introduction

Concrete technology has advanced to overcome the limitations of conventional concrete, such as High-Performance Concrete (HPC). The primary weaknesses of this material include its brittleness, low tensile strength, and crack propagation. Thus, the concept of Fiber Reinforced Concrete (FRC) was created to prevent crack propagation in HPC by reinforcing the cementitious matrix with various fibers, such as steel fibers, glass fibers, synthetic fibers, polyethylene fibers, and carbon fibers. Concrete casting can also be challenging for engineers. This challenge can involve difficult-to-reach structural forms, thereby impacting the concrete quality. Self-Compacting Concrete (SCC) was developed to address this issue, providing benefits such as reaching all corners without using vibrators during casting and reducing noise at construction sites [6]. Therefore, engineers from France have developed Ultra High-Performance Concrete (UHPC) as a new technology, combining HPC, FRC, and SCC as in Fig. 1.

Although UHPC applications are growing, efforts must continue to overcome obstacles hindering their development. Currently, UHPC production methods are being simplified by replacing expensive components like cement, steel fibers, and silica fume with affordable local resources [8].

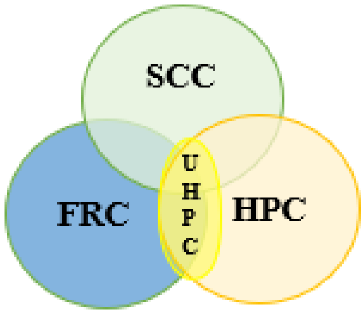

Fig. 1 *Ultrahigh-performance concrete (UHPC)*

Therefore, the present study aims to research UHPC by modifying materials with local materials (localization) to ensure that UHPC can be applied in Indonesian building structures without compromising flowability and quality. Common problems with concrete structures in Indonesian construction include cracking, scaling/spacing, pitting, and honeycombing, which can affect comfort and function and degrade concrete quality. Therefore, short-term repairs are necessary. One repair method is grouting, which, according to ASTM C109-C109M-08, requires repair times of 1, 3, and 7 days with the specified compressive strength requirements. Therefore, we aimed to study the compressive strength at 1, 3, and 7 days on UHPC with the goal of using it for concrete repair.

UHPC is a type of concrete with very high compressive strength and a dense structure. This is due to the increased use of cement compared to regular concrete and a very low water-cement ratio (w/c) of about 0.2, with coarse aggregates omitted from the mix, using only fine aggregates with particle sizes of 0.125 – 0.5 mm. To support the low w/c ratio, superplasticizers are used [23]. The use of superplasticizers compensates for the reduction in water, enhances cement bonding, and results in a slump value with easy workability, setting time, and higher compressive strength than normal concrete [2].

Superplasticizers are admixtures added to concrete mixtures to improve their flowability and workability of the mix. Superplasticizers reduce the viscosity of concrete, allowing the mix to flow more smoothly and be easier to handle. In developing UHPCs, selecting the appropriate superplasticizer and its composition is crucial. Therefore, the composition of various superplasticizer variants is important for improving UHPC quality. However, this must be accompanied by the correct superplasticizer dosage; excessive superplasticizer dosages, especially those with high water content, can lead to nonuniform concrete mixtures and ultimately segregation [1]. Among the various types of superplasticizers, two are compared for their effect on the early compressive strength of UHPC: Naphthalene (SNF) and Polycarboxylate (PCE).

Previous research has investigated the use of superplasticizers in conventional concrete, but studies focusing on UHPC are still limited. Therefore, this research aims to fill this knowledge gap by exploring the effects of different superplasticizer compositions on UHPC parameters, specifically, flowability and early compressive strength [26]. Furthermore, a deeper understanding of the interactions between UHPC components and superplasticizers can contribute to the development of more effective and optimal concrete formulations. By deepening this knowledge, it is hoped that an optimal superplasticizer composition formula can be developed to achieve good flow properties in UHPC.

Through a comparative study of superplasticizer composition in UHPC, this research is expected to contribute to our understanding of the factors affecting UHPC performance. The results of this study are expected to provide practical guidance for the construction industry in optimizing UHPC formulations for infrastructure projects requiring high durability and structural strength. The author and research team conducted preliminary research to study the flow behaviour of various binders with constant superplasticizers and constant w/c ratios. From this preliminary research, material compositions were obtained as a reference for the research to be conducted. The research conducts trials to find the optimum Vb/V value and to test the UHPC

2. Materials and Methods

2.1 Materials

The UHPC composition consists of a high binder content of Portland cement and supplementary cementitious materials (SCMs), such as fly ash and limestone. A coarse aggregate is removed from the UHPC mix to avoid high porosity and to create a dense interfacial transition zone around the aggregate, thereby eliminating the weakest areas in the matrix [5]. The coarse aggregate was replaced with well-graded fine sand to ensure high packing density. The UHPC mix design incorporates two types of chemical admixtures: high-range water reducers (superplasticizers) and concrete accelerators. Finally, micro sized fibres were added to enhance the strength of the mixture.

The materials used in this experimental work are described as follows:

- Cement (OPC type I) confirming SNI 2049-2015 and ASTM C150 supplied by PT. Solusi Bangun Indonesia (SBI).
- Fly Ash (type F) confirming to ASTM C618-19 supplied by PT. PLN Nusantara Power (UP Tanjung Awar-Awar.
- Limestone (CaCO3) Mesh 3000 and Mesh 5000 supplied by Niraku Jaya Abadi.
- Good quality and well-graded river sand with a maximum size of 4.75 mm was used during this experimental work, supplied by Lumajang.
- Sika Viscocrete 3115N, a poly-carboxylate ether- based superplasticizer, was used as a high-range water-reducing admixture, commercially manufactured and supplied by Sika Indonesia.
- Sulfonated Naphthalene Formaldehyde (SNF), a naphthalene-based superplasticizer, was used as a high-range water-reducing admixture.
- Polyamide Fibers supplied by Sika Indonesia.

Table 1 lists the compositions of the cement and fly ash samples, and Table 2 lists the characteristics and properties of the superplasticizer PCE and SNF used during this experimental work.

Table 1 *Physical and chemical characteristics of cement and fly ash*

Chemical characteristics	Cement	Fly Ash
SiO_2 (%)	19.45	47.51
Al_2O_3 (%)	5.38	19.27
Fe_2O_3 (%)	2.95	18.46
CaO (%)	65.13	8.89
MgO (%)	2.35	3.77
SO_3 (%)	2.06	0.77

Table 2 *Properties and characteristics of superplasticizer*

The types of SP	Dry Matter	Color	Density (kg/m^2)
PCE	>30%	Yellowish Liquid	1050
SNF	15-25%	Brown Powder	1170

2.2 Mixed Proportions

The mixing process for UHPC is significantly different from that of conventional concrete mixing. UHPC typically contains minimal water and little to no coarse aggregate. According to ACI 239R-18, the process begins by thoroughly mixing the dry components before adding water and a High-Range Water Reducer (HRWR). Mixing time varies depending on the mixer's energy, with high-energy mixers requiring just a few minutes while low-energy mixers may need 20 min or more. The use of high-energy input is necessary to ensure proper mixing, which might require adjustments to prevent overheating, such as using ice water. The mixing time ranged from 7 to 18 min, which is longer than that of conventional concrete. Graybeal [12] notes that UHPC mixing demands higher energy, affecting the procedures, duration, and equipment used. In the future, an electric concrete mixer will be used for UHPC mixing. Table 3 lists the specifics of each mix. The reference mix did not contain any mineral admixtures. Trials were also conducted to determine the optimum dosage of the superplasticizer to achieve a target slump around 200-250 mm. The dosages were carefully selected to reduce the adverse effects of overdose.

Table 3 *UHPC composition ratio*

Num	UHPC Composition Materials	*Superplasticizer Polycarboxylate* Ether (PCE)			*Superplasticizer* Sulfonated *Naphthalene* Formaldehyde (SNF)		
		1	2	3	4	5	6
1	Ordinary Portland Cement	1.00	1.00	1.00	1.00	1.00	1.00
2	LS Mesh 3000	0.06	0.06	0.06	0.06	0.06	0.06
3	LS Mesh 5000	0.06	0.06	0.06	0.06	0.06	0.06
4	Fly Ash	0.48	0.48	0.48	0.48	0.48	0.48
5	Water	0.32	0.32	0.32	0.32	0.32	0.32
6	SP	0.016	0.024	0.032	0.016	0.024	0.032
7	Lumajang sand	1.30	1.31	1.32	1.30	1.31	1.32
8	14-40 sand	0.87	0.88	0.89	0.87	0.88	0.89
9	Fiber (Polyamide)	0.004	0.004	0.004	0.004	0.004	0.004

2.3 Sample Preparation

After mixing, it is necessary to continue with concrete maintenance to maintain the quality of the concrete. Curing of concrete refers to the treatment applied to freshly hardened concrete. The purpose of curing is to maintain the moisture and temperature of the concrete, allowing the hydration process to proceed properly and preventing surface cracking. Curing is another factor that can influence the compressive strength of concrete [19]. According to Raheem et al. [24], curing is a process used to control the rate and moisture content of concrete during cement hydration. Curing also reduces water evaporation from the concrete, ensuring sufficient moisture content within the concrete.

Based on ACI 239R-18, the curing method can affect the material properties of UHPC. Certain types of UHPC require curing methods that involve specific high temperatures and humidity levels for a certain period. UHPC can be subjected to heat treatment, pressure, or both at this stage. This can increase density, reduce air trapped, remove excess water, and accelerate chemical shrinkage. According to J. Du et al. [10] reported that UHPC subjected to moist curing can achieve a compressive strength of ≥ 120 MPa.

The steps for UHPC treatment are: After mixing, fresh UHPC is immediately inserted into the mold, Remove the test object mold 24 hours after mixing, fill the curing box using 3 g/L calcium hydroxide (CaOH) solution (Figure 2), and remove the test object 1 day before the planned test age.

Fig. 2 *Curing of specimens in curing boxes*

2.4 Test Methods

Quality testing for UHPC in the United States generally uses the same tests as those used for conventional concrete or mortar with or without modification.

2.4.1 Flowability Test

UHPC flow is often measured using ASTM C1856-C1856M - 17. In this test, the initial and dynamic flows were measured. The test was completed immediately after mixing to assess the consistency of the mixture and its suitability for casting. The slump flow test was performed 5 min after mixing to remove any remaining gases in the concrete. The UHPC mortar was then placed into a Haegermann cone on a dry glass plate, as shown in Figure 3**.** Two minutes after the cone is removed, two diameters of the concrete spread are measured perpendicular to each other and recorded [15].

Fig. 3 *Haegermann cone*

2.4.2 Early Compressive Strength Test Results

UHPC compressive strength testing is often performed using a modified version of ASTM C39 [29]. The test method was modified to include an increase in the load rate to 150 psi/s (1 MPa/sec) in response to the high compressive strength of UHPC. Proper preparation of the cylinder ends is critical because uneven or misaligned end surfaces can reduce the observed compressive strength. Graybeal reported that a 3 by 6inch (76 by 152 mm) cylinder demonstrated strength similar to a 4 by 8inch (102 by 203 mm) cylinder while allowing for a significantly reduced testing machine capacity.

The ASTM C39-C39M-01 test determines the compressive strength of cement based on its cylindrical size. The working steps of the UHPC compressive strength test are as follows: Prepare the test specimen, Place the test specimen on the bottom plate of the compression testing machine, Place plywood on top of the test specimen so that the surface of the test specimen is flat, as in Figure 4, Run the compression testing machine at a speed between 200 and 400 pounds per second until damage occurs to the sample, record the maximum load that occurs, Test at least three samples, and average the data.

Fig. 4 *Compressive strength testing machine*

2.4.3 UHPC Testing Targets

In this study, UHPC had a target value in each test, which can be seen in Table 4.

Table 4 *UHPC testing targets*

Testing	Target Value	References
Flowability	200–250 mm	ASTM C1856-C1856M
Early Strength		
1 day	24 MPa	ASTM C109-C109M - 08
3 days	40 MPa	
7 days	52 MPa	

3. Results and Discussion

The results and discussion of all research activities starting with the mix design up to the results of the implementation in the laboratory, which includes flowability testing and early compressive strength testing, are presented in the form of tables, graphs, and discussions.

3.1 Flow test results

After the UHPC manufacturing process was completed, flowability testing was carried out using a flow table. The test results are shown in Table 5 and Figure 5.

Table 5 *Flow values for each variation*

Superplasticizer Variations	Unit	Flow Value
V1. PCE 1%	mm	190
V2. PCE 1,5%	mm	200
V3. PCE 2%	mm	210
V4. SNF 1%	mm	100
V5. SNF 1,5%	mm	110
V6. SNF 2%	mm	110

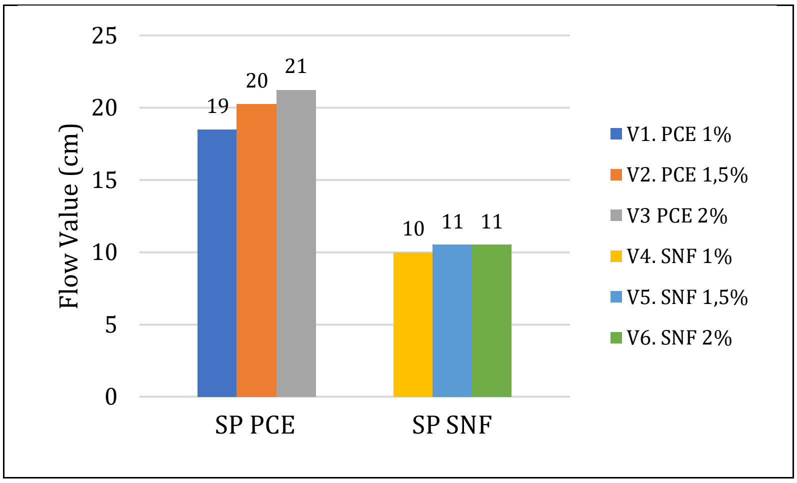

Fig. 5 *Flow value graph based on superplasticizer type and composition*

Based on the research, it was found that the greater the composition of the superplasticizer added to UHPC with the same w/c ratio, the higher its flowability [7]. This result aligns with the flowability test results (Table 5). Additionally, Khayat et al. used a polycarboxylate ether superplasticizer in their mix-design calculations.

The results of this study indicate that adding a polycarboxylate superplasticizer to UHPC results in higher flow compared to sulfonate naphthalene formaldehyde (SNF). The use of polycarboxylate superplasticizers with concentrations of 1.5% and 2% meets the ASTM C1856/C1856M-17 flow requirements of 20 and 21 cm. The flow test showed that polycarboxylate superplasticizer increased the flow by 1-2 cm or 4%-10%, indicating that higher superplasticizer content enhances UHPC workability. In contrast, the SNF superplasticizer resulted in flow values significantly below the required range, at 10-11 cm.

Figure 5 shows that the polycarboxylate superplasticizer performs much better in terms of flow than SNF. The chemical mechanisms of PCE and SNF, highlighting that PCE excels at dispersing cement particles, preventing agglomeration, and thus reducing flow resistance, whereas SNF is less effective at dispersing cement particles, leading to potential agglomeration [33].

3.2 Early Compressive Strength Test Results

The results of early compressive strength testing on UHPCs conducted at 1, 3, and 7 days of age with variations in the types and compositions of the superplasticizers are presented in Table 6.

Table 6 *Early compressive strength test results*

Variation	Average Compressive Strength (MPa)		
	1 day	3 days	7 days
V1. PCE of 1%	20.6	58.1	62.5
V2. PCE of 1.5%	38.3	50.1	71.7
V3 PCE of 2%	0.2	51.1	63.4
V4. SNF 1%	2.9	37.9	39.5
V5. SNF 1,5%	19.2	38.5	39.2
V6. SNF 2%	8.5	31.0	34.6

In addition to influencing the flow values, superplasticizers affect the early compressive strength of UHPC. In some cases, superplasticizers may reduce early strength due to retardation effects. However, this effect can usually be controlled, and the final strength of the concrete is not affected or may even increase [16]. Some superplasticizers, especially at high concentrations, can delay the initial hydration of cement due to the adsorption of superplasticizer molecules on the surface of cement particles, thereby slowing the early strength development of UHPC [22].

Thus, the results of early compressive strength tests are consistent with those of other studies, where, in Table 6, a 2% dose of PCE and SNF superplasticizers resulted in the lowest compressive strength compared with 1% and 1.5% doses of each type of superplasticizer. The use of PCE superplasticizers in UHPC is more optimal in terms of early compressive strength compared to SNF superplasticizers, indicating that the UHPC with the highest early compressive strength was Variation 2, with a PCE superplasticizer composition of 1.5%, resulting in a linear increase in early compressive strength compared to the other variations. The average compressive strength at 7 days was 71.7 MPa.

Therefore, the use of different types and compositions of superplasticizers can influence the early compressive strength of UHPC, as explained in Salem et al. (2016) study UHPC, which states that there is an optimum dosage limit for superplasticizer use; exceeding this limit can lead to a reduction in early compressive strength [25]. This is also explained by [20], who note that exceeding 1.5% in the mix leads to poor UHPC workability due to particle agglomeration in the presence of fibers [20]. This occurs because at higher superplasticizer doses, the hydration process is not only uninterrupted but also accelerated by the additional water from deflocculation (uniform distribution) of cement particles. Therefore, increasing the dosage enhances trapped water and cement hydration.

3.3 Influence of Superplasticizer Type and Composition on the Flowability and Early Strength of UHPC

UHPC has a material composition that is different from that of conventional concrete, including OPC cement, limestone, fly ash, fine sand, fibers, and water, with the addition of superplasticizers to reduce water demand and improve workability. However, different types and compositions of superplasticizers can have different effects on UHPC properties. Good flowability is crucial for a low water-cement ratio. Increased flowability reduces porosity and enhances microstructure density, leading to higher early compressive strength. The correct superplasticizer and optimal dosage are critical for achieving excellent flowability and early UHPC strength.

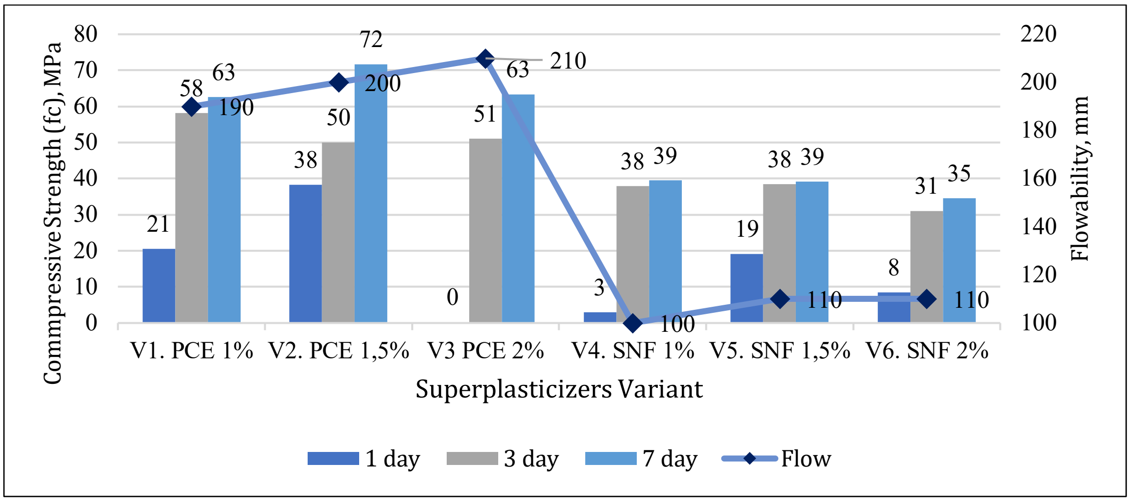

Fig. 6 *Flowability and early strength test results of UHPC*

Based on Figure 6, the optimum result was obtained using the PCE-type superplasticizer at a 1.5% dosage. Although the flow result for the PCE superplasticizer at a 2% dosage was the highest compared with the others, the early compressive strength decreased due to exceeding the optimum dosage of the superplasticizer. As explained in Zhang & Kong (2015), this occurs because the superplasticizer works by coating cement particles, which can slow down the hydration process if used in excessive amounts. Such impaired hydration leads to slower or lower early strength development than expected [33].

The increase in flowability achieved using superplasticizers is usually positively correlated with the early compressive strength, provided that the water-cement ratio remains low. In other words, UHPC that flows well (high flowability) and has an even distribution of cement tends to exhibit increased early compressive strength. Although high flowability is desirable, it's essential to control superplasticizer usage carefully. Excessive flowability can lead to segregation, which damages the concrete's structural integrity and reduces its compressive strength [21]. In conclusion, there is a positive correlation between flowability and early compressive strength in UHPC when superplasticizers are properly used. Superplasticizers allow for increased flowability without water addition, contributing to enhanced early compressive strength through reduced water-cement ratios and improved cement particle distribution.

4. Conclusions

The effect of superplasticizer composition and variants on UHPC flowability is that as the superplasticizer composition increases for UHPCs with the same w/c ratio, the flowability value also increases. The use of different types of superplasticizers can also affect the flow value, as each type has a different water reduction capacity. PCE (Polycarboxylate Ether) has a water reduction characteristic of >30%, while SNF (Sulfonated Naphthalene Formaldehyde) has a water reduction characteristic of 15-20%. Another reason is related to the chemical mechanisms of PCE and SNF. PCE superplasticizers have the advantage of finely dispersing cement particles, preventing agglomeration. The particles were coated with PCE to reduce the flow resistance. On the other hand, SNF superplasticizers are less effective at dispersing cement particles, thus allowing for potential agglomeration. Regarding the effect of superplasticizer composition and variants on early strength, as the superplasticizer composition of UHPC increased, the early strength value also increased. However, if the superplasticizer composition exceeds the optimum dosage, the compressive strength. It was found that among the PCE and SNF superplasticizers, the PCE superplasticizer with a composition of 1.5% was the optimal for UHPC mix design. This is because it has a flow value that meets ASTM C1856 - C1856M – 17, which is in the range of 200-250 mm, and it has the highest early compressive strength at 7 days (71.7 MPa), as well as a linear increase in compressive strength compared to other types and compositions.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors are responsible for the study conception, research design, data collection, data analysis, result interpretation and manuscript drafting.

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