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THE INFLUENCE OF W/C AND SUPERPLASTICIZER ON THE COMPRESSIVE STRENGTH OF HSCP CEMENT PASTES

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ABSTRAK

Penelitian ini mengkaji pengaruh variasi faktor air-semen (W/C 0,10–0,30) dan dosis superplasticizer PCE (0,6%–141%) terhadap kuat tekan pasta semen mutu tinggi, serta menentukan komposisi optimal dan efisiensi biayanya. Metode eksperimental laboratorium menggunakan 18 variasi campuran dengan benda uji kubus 5x5x5 cm, diuji pada umur 7, 14, dan 28 hari. Hasil menunjukkan hubungan tidak linier. Pada W/C 0,30, kebutuhan SP hanya 0,6–2%, sedangkan pada W/C 0,10, dosis SP melonjak drastis hingga 141% untuk mempertahankan workability. Komposisi optimal ditemukan pada W/C 0,22 dengan SP 5% (RUN 14), menghasilkan kuat tekan maksimum 42 MPa (28 hari) dan 43 MPa (7 hari), di mana kekuatan 7 hari lebih tinggi karena percepatan hidrasi awal. Overdosis SP (≥35%) justru menurunkan kuat tekan secara signifikan menjadi 15 MPa dan 8 MPa akibat segregasi, bleeding, dan hambatan hidrasi berlebih. Analisis kurva tegangan-regangan menunjukkan transisi perilaku dari daktil menjadi getas. Korelasi positif antara densitas dan kuat tekan terbukti pada rentang optimal (1900–2000 kg/m³). Analisis RAB menunjukkan total biaya Rp2.390.000 dengan efisiensi terbaik pada komposisi optimal (Rp56.904/MPa), jauh lebih hemat dibanding overdosis (>Rp150.000/MPa). Kesimpulannya, W/C 0,22 dan SP 5% direkomendasikan sebagai komposisi paling ekonomis dan berkinerja tinggi untuk infrastruktur berkelanjutan.

Kata kunci : HSCP, FAS, Superplasticizer, Kuat Tekan, RAB.

ABSTRACT

This study examines the effect of water-cement factor variation (W/C 0.10–0.30) and PCE superplasticizer dose (0.6%–141%) on the compressive strength of high-quality cement paste, and determines its optimal composition and cost efficiency. The laboratory's experimental method used 18 mixed variations with 5x5x5 cm cube test specimens, tested at 7, 14, and 28 days of age. The results show a nonlinear relationship. At W/C 0.30, the SP requirement is only 0.6–2%, while at W/C 0.10, the SP dose jumps dramatically to 141% to maintain workability. The optimal composition was found at a W/C of 0.22 with an SP of 5% (RUN 14), resulting in a maximum compressive strength of 42 MPa (28 days) and 43 MPa (7 days), where the strength was 7 days higher due to the acceleration of initial hydration. An overdose of SP (≥35%) actually significantly reduced compressive strength to 15 MPa and 8 MPa due to segregation, bleeding, and excess hydration resistance. Analysis of the stress-strain curve showed a behavioral transition from ducttile to brittle. A positive correlation between density and compressive strength is evident in the optimal range (1900–2000 kg/m³). RAB analysis showed a total cost of Rp2,390,000 with the best efficiency at the optimal composition (Rp56,904/MPa), much more economical than overdose (>Rp150,000/MPa). In conclusion, W/C 0.22 and SP 5% are recommended as the most economical and high-performance compositions for sustainable infrastructure.

***Keywords** : HSCP, FAS, Superplasticizer, Kuat Tekan, RAB.*

1. INTRODUCTION

Sustainable infrastructure development today demands material efficiency and longer service life through the use of innovative materials such as High-Strength Cement Paste (HSCP) developed to produce high mechanical performance while supporting the efficiency and sustainability of modern construction [1].

[2] states that modern structures require materials with mechanical properties and durability that exceed conventional standards in order to be able to adapt to increasingly challenging environmental conditions. The achievement of superior material performance is highly dependent on the selection of the right constituent materials as well as the control of microstructures. The achievement of this outstanding performance relies heavily on the precise selection of constituent materials and modifications at the microstructural level to create a matrix that is dense, resilient, and capable of maintaining structural integrity over the long term. [3].

Although research on High-Strength Concrete (HSC) has grown rapidly, most studies still focus on evaluating the overall macrostructural properties of concrete, such as compressive strength and global durability performance [4]. Many studies have focused on the optimization of the composition of the mixture, the use of *supplementary cementitious materials*, and predictive modeling to achieve specific mechanical strength targets, without an in-depth study of the microstructural mechanisms that occur in the cement paste phase [4].

This approach often ignores the fundamental behavior of its binding phase, which is hardened cement paste, which plays a dominant role in the load transfer mechanism and the control of material degradation. Recent research shows that the microstructural characteristics of cement paste, including matrix densification rates and pore distribution, have a significant influence on the mechanical properties and durability of concrete [5].

Recent developments in superplasticizer technology show that the formulation of*polycarboxylate ether*(PCE) composites reinforced with nanomaterials, specifically surface-modified nano-silica, significantly improve the mechanical and functional properties of cement mixtures. For example, research by [6] successfully synthesized*nanosilica-doped polycarboxylate superplasticizer*(NS/PCE) through nano-silica grafting reactions into the PCE molecular chain, where the results show that NS/PCE has a higher adsorption capacity and better dispersion ability against cement particles than PCE without nano-silica doping, In addition, the quality of the PCE *Interfacial Transition Zone* (ITZ) between the paste and the aggregate has also been shown to be a key factor controlling the strength and durability of high-performance concrete, where a denser and more homogeneous ITZ is able to increase the strength as well as resistance to the penetration of aggressive substances [7]. Therefore, an in-depth study of the microstructure behavior of hardened cement paste and ITZ is an essential aspect in the development of high-performance concrete.

This study is designed to fill the gap in the study by examining the effect of the interaction of Cement Water Factor (W/C) and Superplasticizer on the compressive strength of HSCP paste cement, The analysis is focused on the mechanism of cement particle dispersion and density of the paste matrix resulting from the reduction of W/C with the help of superplasticizer**.** By investigating the relationship between the optimization of the mixture composition and cost efficiency, the study aims to recommend a high-performance material formulation that can improve the reliability and service life of high-performance structures in the context of sustainable Indonesian construction.

2. METHODS

This study is a laboratory quantitative experimental study with a factorial approach to investigate the effect of water-cement factor variation (W/C) and superplasticizer (SP) dose on the compressive strength of High-Strength Cement Paste (HSCP). The research was carried out at the Construction Materials Technology Laboratory, Department of Civil Engineering, Malang State Polytechnic, with a duration of 4 months including the preparation stage, making test objects, maintenance, compressive strength testing, and data analysis.

The main materials used are Portland cement type I (PCC) which meets SNI 7064:2014 standards, commercial polycarboxylate ether (PCE) type superplasticizer Sikament LN (PT. Sika Indonesia), and clean water from the Malang City PDAM network. Superplasticizers are used in a dose range of 0.6%–141% to cement weight, while W/C variations are set between 0.10–0.30.

The Taguchi method is an approach in quality engineering that aims to obtain the best combination of factors in a production process, in order to produce products with optimal quality and minimal variation. The basic philosophy is to design quality from scratch through systematic experimentation, so that the product becomes sturdy or resistant to noise factors that are difficult to control. This method emphasizes that improving quality can actually lower overall production costs, as it reduces product waste and mismatches [8].

1. Portland Cement

Cement is a hydrolytic binding agent that reacts with water to form solid hydration products, especially Calcium Silicate Hydrate (C–S–H), which plays a dominant role in providing the strength and structural stability of cement-based materials [9]. The typical composition of Portland cement includes approximately 97% clinker and 3% limestone or gypsum, with the main oxide content being calcium oxide (CaO), silica (SiO2), alumina (Al2O3), and iron oxide (Fe2O3) [10].

Figure 1. Cement PCC type 1
Sumber: Hasil Analisis

2. Superplasticizer

Superplasticizers are state-of-the-art chemical additives (admixtures) that are added to concrete mixtures with low percentages to drastically reduce water requirements or increase workability without the addition of water [11]. This capability is particularly critical in the production of High-Strength Cement Paste (HSCP), as it enables the use of very low water-to-cement ratios necessary for achieving superior compressive strength while maintaining adequate workability for proper mixing and compaction.

Figure 2. Superplastcizer
Source: Analysis Results

The mixed design consists of 18 variations with details: four variations at W/C 0.30 with a dose of SP 0.6%; 0,8%; 1,3%; and 1.5%; five variations at W/C 0.29–0.25 with a fixed SP of 1.5% (except W/C 0.25 with an SP of 3% and 6%); and nine variations at W/C 0.24–0.10 with a dose adjustment of SP of 4%–141%. Each variation is made of 3 test pieces, so that the total test pieces are 54 units plus 6 spares.

The cube shaped test specimen measuring 5×5×5 cm refers to SNI 03-6825-2002. The manufacturing process begins with weighing the material using a digital scale with an accuracy of 0.01 grams. The superplasticizer is emulsified with stirring water for 5 minutes until homogeneous. The cement is put into the mixing container, then the stirring liquid is gradually added while stirring until a homogeneous cement paste without clumps is obtained. The paste is molded in an oil-lubricated silicone mold, treated in a humid chamber for 24 hours, then removed from the mold and immersed in a treatment tub for a test life of 7, 14, and 28 days.

Compressive strength testing is carried out with a universal compressive testing machine. Before loading, the test specimen is weighed to determine the initial mass and density. A dial indicator (LVDT) is mounted on the frame of the test machine to measure the change in vertical length during loading. The load is applied gradually at a constant speed until the test specimen is destroyed. Peak load and strain data are recorded for compressive strength calculation with formulas.

$$\sigma = \frac{P}{A} \tag{1}$$

Strain (*strain*, denoted by ε) is a measure of the relative deformation of a material due to loading, defined as the change in length per initial unit length. Mathematically, axial stretches are expressed as.

$$\varepsilon = \frac{\Delta L}{\mathrm{L0}} \tag{2}$$

where ε is the strain (without dimensions or mm/mm), ΔL is the change in the length of the test specimen (mm), and L_0 is the initial length of the test specimen (mm).

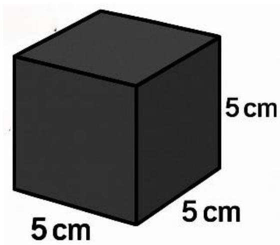

Figure 3. Cube Specimen
Source: Analysis Results

Fig 3. Shows The design of the Portland cement mortar cube specimen with a size of 5x5x5 cm is used for mortar compressive strength testing, referring to the provisions of SNI 03-6825-2002. Mortar specimens are prepared based on the composition of the mixture listed in Table 3.1, where each variation of the mixture is made as many as three (3) specimens to ensure repeatability and reliability of the test results. Thus, the total number of mortar cube specimens used in this study is 34 specimens.

Figure 4. Compressive Strength Test Machine
Source: Analysis Results

Compressive strength testing on cement paste samples aims to evaluate the quality of the material produced from the mixing and curing processes that have been applied. Before the loading process begins, each test specimen is weighed using a digital scale to determine its initial mass. This initial weighing is important as supporting data in analyzing the density of the specimen as well as the correlation between mass and compressive strength produced.

Fig 4. shows the initial preparation stage and setting of the compressive strength test of HSCP specimens. The digital indicator dial has been mounted on the frame of the pressure test machine and set to the zero position (0.00 mm) after the upper press plate has touched the surface of the specimen without providing a load. A 50×50×50 mm cube specimen labeled "RUN 2c" is placed right in the center of the pressure plane of the testing machine to ensure even axial loading. The pressure testing machine is ready for operation with a digital indicator indicating the standby condition before the loading process begins.

Furthermore, the preparation and calibration of the pressure test device was carried out. The surface of the press test equipment is cleaned of material residues or debris that may affect the test results. In addition, the position of the base (press plate) is checked and ensured that it has been installed correctly according to the applicable test standards, for example SNI 03-6825-2002.

The installation of the digital indicator dial (LVDT or dial gauge) is carried out at a predetermined position on the pressure test machine frame to measure the change in the vertical length of the specimen during the loading process, then the initial setting (zero setting) is carried out by pressing the ZERO/SET button on the digital panel after the upper pressure plate touches the surface of the specimen without providing a load (initial contact condition) to ensure that all subsequent strain readings are relative changes of length At the beginning of the specimen, as well as position verification is carried out so that the indicator dial is perpendicular to the pressure plane and does not occur tilt or eccentricity that can affect the accuracy of the reading.

After the tool is ready, the test piece is installed at the center of the test tool by placing the paste sample right in the center of the pressure field of the test machine. Once the position is precise, the tool's locking mechanism is activated to prevent shifting during the loading process.

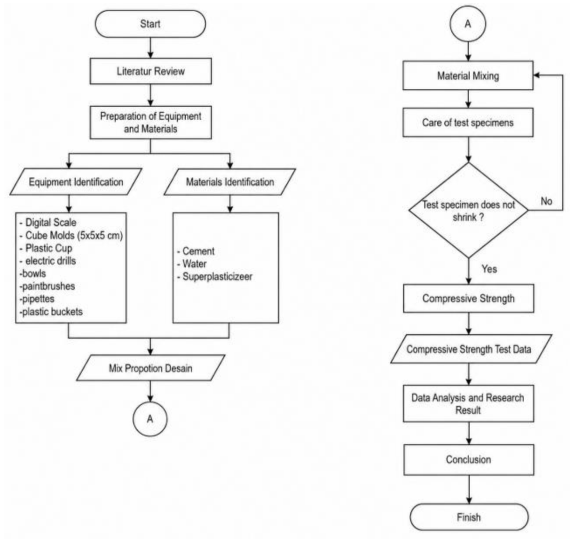

Figure 5. Flowchart
Source: Analysis Results

Fig 5. presents a methodical and sequential experimental protocol designed to investigate the behavior of cement paste modified with a superplasticizer. The process begins with a foundational literature review, ensuring that the research is grounded in established theory before any practical work commences. This is followed by a stringent preparation phase, where both equipment and materials are meticulously identified and cataloged ranging from basic mixing tools like bowls and drills to precise instruments such as digital scales and pipettes highlighting the importance of measurement accuracy and standardized conditions.

3. RESULTS AND DISCUSSION

A. The Relationship of Superplasticizer and Cement Water Factor

The relationship between the cement water factor (W/C) and the dose of the superplasticizer (SP) showed a nonlinear pattern. At W/C 0.30, the SP requirement is only 0.6%–2% by weight of cement. However, when the W/C was lowered to 0.10, the SP dose increased drastically to 141% to maintain workability. This happens because at very low W/C, the amount of free water that functions as a lubricant between cement particles is very limited, so a high SP dose is required to disperse cement particles through electrostatic and steric rejection mechanisms.

The regression analysis yielded the equation SP = 122.31 – 440.84(W/C) with an R-Square value of 0.594. The ANOVA test showed a Significance F value of 0.00011 ($p < 0.05$), which statistically proves that the effect of W/C on SP dose is very significant.

B. Effect of SP Dose Variation on Initial Compressive Strength

The effect of SP dose variation on the development of initial compressive strength of HSCP was evaluated at 7, 14, and 28 days of age. In the low dose range (0.6%–1.5%) with a constant W/C of 0.30, the compressive strength pattern fluctuates and is unstable. SP 0.8% recorded a drastic decrease from 39.44 MPa (7 days) to 17.48 MPa (14 days), while SP 1.3% degraded at 28 days (17.61 MPa) after increasing at 14 days (37.77 MPa). This pattern shows that the SP dose of 0.6%–1.5% is not optimal for W/C 0.30 because the dispersion of cement particles is uneven due to the relatively high availability of water.

In the wide dose range (2%–141%), a clear optimal pattern is seen. The 8% SP with a W/C of 0.20 reached the highest and stable compressive strength of 40.89 MPa (28 days), while the 35% and 141% SP over-doses experienced severe degradation (6.65–8.15 MPa) due to segregation and hydration inhibition.

However, exceeding this threshold induces excessive fluidity, leading to particle segregation and the formation of free water layers, which not only disrupts the homogeneous distribution of hydration products but also retards the pozzolanic reaction due to the dilution of the pore solution's ionic concentration. Consequently, these findings suggest that for low W/C mixtures, SP optimization should prioritize achieving a saturated adsorption point on the cement particles, beyond which any additional dosage yields diminishing returns and ultimately proves detrimental to long-term mechanical performance, reinforcing the necessity of tailoring the SP content precisely to the specific W/C ratiorather than applying a uniform dosage across all mix designs

C. Optimal Composition for Maximum Compressive Strength

Based on all test data, the optimal composition was obtained at RUN 14 with a W/C of 0.22 and an SP dose of 5%, resulting in a maximum compressive strength of 42 MPa at 28 days of age and 43 MPa at 7 days of age. The material composition in RUN 14 is 81.00% cement, 17.80% water, and 1.20% superplasticizer.

The recommended optimal range for HSCP applications is W/C 0.20–0.23 with an SP dose of 3%–8%, capable of producing a compressive strength of 35–43 MPa. Outside of this range (W/C ≤ 0.18 or SP ≥ 35%), there is a degradation of compressive strength up to 8–15 MPa. The 28-day lifetime compressive strength distribution map visualizes the optimal zone with dark green color concentrated in the W/C range of 0.20–0.23 with an SP of 5%–8% (41–42 MPa), while red/orange indicates low strength (< 15 MPa) under extreme conditions.

A comparison of the material proportions in the three strength groups showed that the High Strength group had the highest proportion of cement (80.97%) with the lowest water (17.81%) and moderate SP (5%). In contrast, the Low Strength group had extreme SP (141%) but cement was lower (89.70%) and water was very minimal (8.97%), indicating that over-dose SP interfered with the ideal material ratio.

Tabel 1. Max *Composition Mixed material*

RUN	Cement (%)	Water (%)	Superplasticizer (%)	Number of Specimens	W/C (Water/Cement)
14	81.00	17.8	5	3	0.22

Source: Analysis Results

Table 1. Shows The SP dose of 5% in RUN 14 was within the previously identified 5% effective range. In this range, the superplasticizer is able to spread the cement particles evenly so that the paste remains easy to work with even though the amount of water is very limited. This result also shows that while W/C 0.22 is the optimal limit in this study, a decrease in W/C below 0.20 (as in RUN 14 with W/C 0.22 and SP 5%) does not increase compressive strength further because the paste becomes too stiff and difficult to compact, resulting in air cavities that damage the strength.

4. CONCLUSION

The effect of the variation in the dose of the superplasticizer on the workability and development of the initial compressive strength of HSCP with a very low water-cement ratio showed a nonlinear relationship. Increasing the SP dose allows for a decrease in W/C from 0.30 to 0.10 without loss of workability, where at W/C 0.30 the SP requirement is only 0.6%–2%, while at a very low W/C (0.10–0.20) the SP dose increases drastically to 8%–141%.

The initial compressive strength of 7 days showed a fluctuating pattern in the low SP dose range (0.6%–2%) with a value of 18–39 MPa, but tended to be stable and increased in the optimal SP range of 3%–8% with a compressive strength of 31–43 MPa.

The optimal composition of the three materials to achieve the maximum compressive strength in HSCP was obtained at RUN 14 with a W/C of 0.22 and a dose of SP of 5% to the weight of cement, with the proportion of cement material 81.00%, water 17.80%, and superplasticizer 1.20%. This composition produces a compressive strength of 43 MPa at 7 days of age and 42 MPa at 28 days of age. The recommended optimal range for HSCP applications is W/C 0.20–0.23 with an SP dose of 3%–8%, capable of producing a compressive strength of 35–43 MPa. Outside this range, there is a degradation of compressive strength up to 8–15 MPa.

The application of the superplasticizer to the optimum point (5%–8%) successfully increased the compressive strength significantly from 25 MPa to 41–42 MPa through a more even dispersion mechanism of cement particles and an increase in the density of the paste matrix with a density of 1900–2000 kg/m³. The excessive use of SP (over-dose ≥ 35%) actually causes the opposite effect with a drastic degradation of compressive strength to 15 MPa (SP 35%) and 8 MPa (SP 141%), accompanied by segregation, bleeding, and delay in hardening. Tension-strain curve analysis showed a transition of mechanical behavior from dactyl at 7 days of age to brittle at 14 and 28 days of age as hydration degrees increased.

The analysis of the Cost Budget Plan (RAB) shows that the total cost of research is Rp2,390,000.00 including materials of Rp550,000.00 and equipment of Rp1,840,000.00. The cost per unit of power in the optimal composition of RUN 14 is Rp56,904/MPa, which is the most efficient ratio compared to other variations. Over-dosing SP on RUN 17 and 18 leads to a waste of costs without a proportionate increase in strength. The total budget is considered very feasible for laboratory-scale research with an output of 60 HSCP test objects.

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