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STUDY ON COMPRESSIVE STRENGTH AND CHLORIDE ION PERMEABILITY OF HIGH FLY ASH CONTENT SELF-COMPACTING CONCRETE

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ABSTRACT: In Vietnam, the annual emission of fly ash from thermal power plants into the environment is substantial. Previous studies have demonstrated that using a high content of fly ash as a fine additive in the production of self-compacting concrete (SCC) can effectively reduce concrete production costs and contribute positively to environmental protection. This article presents the results of experimental research on the influence of high fly ash content on workability, compressive strength, and chloride ion permeability of SCC. The research involved substituting a portion of cement with fly ash at proportions of 50% and 60%, respectively, and the results were then compared with control samples without fly ash ("control samples"). The experimental findings indicate that using 50% and 60% high fly ash content can produce SCC mixtures with excellent workability, meeting the requirements outlined in the European guidelines, and significantly reducing the superplasticizer dosage compared to control samples. However, employing high fly ash content at 50% and 60% resulted in a reduction in compressive strength at the 28th day of age for SCC, ranging from 19.86% to 30.49% compared to the control sample. At the 90th day of age, the compressive strength increased by approximately 22.2% to 24.5% compared to the 28th day value. Furthermore, the use of high fly ash content also notably reduced the chloride ion permeability of SCC in later stages (i.e., after 28 days). The reduction ranged from 71.97% to 83.72% on the 28th day and from 92.76% to 94.07% on the 90th day, compared to the control sample. The chloride ion permeability of SCC containing 50% and 60% fly ash falls within the category of very low permeability. This research sheds light on the potential incorporation of high fly ash content in SCC production, providing insights into its workability and environmental benefits while considering the impact on compressive strength and chloride ion permeability.

Keywords: Self-compacting concrete, Workability, Concrete strength, Chloride ion permeability

1. INTRODUCTION

Self-compacting concrete (SCC) is a specialized type of concrete known for its high consistency and excellent workability. SCC can auto-flow through the formwork without the need for external vibration, thereby ensuring a dense and well-compact structure [1]. Using SCC offers numerous benefits, such as faster construction, reduced dependency on labor and equipment, improved working conditions for workers, noise reduction, and environmental protection. However, the cost of materials and quality control of SCC remains higher than that of traditional concrete [2].

Fly ash is the most commonly used fine additive in SCC production [3]. Utilizing a high content of fly ash as a partial replacement for cement in SCC is a reasonable option to reduce costs and make concrete more eco-friendly. According to a study [4], SCC with 50% fly ash can achieve compressive strength ranging from 20-40MPa with costs comparable to that of traditional concrete. Furthermore, [5] defines concrete with fly ash content exceeding 50% as high fly ash content concrete.

Global research has shown that using a high fly ash content can influence SCC's properties. As reported by Jalat [6], the use of high fly ash content enhances the flowability of SCC, affecting its rheological behaviors. Another study [7] demonstrated that SCC with high fly ash content has a prolonged setting time compared to non-fly ash SCC. However, high fly ash content may slow down the cement hydration process, leading to a decrease in the early-age mechanical properties of SCC [8]. The mechanical strength of SCC with high fly ash content reaches its maximum at the 90th day of age [9]. Moreover, the presence of high fly ash content helps prevent chloride ion intrusion into SCC [10, 11]. Research [12] also indicated that SCC containing fine additives has a more uniform and denser structure compared to SCC without additives. The use of 40%-60% fly ash helps reduce water permeability, water absorption, and chloride ion permeability of concrete [13]. Additionally, using a high fly ash content in SCC improves its resistance to sulfuric acid attack [14].

In Vietnam, thermal power plants annually release approximately 13 million tons of fly ash into the environment, of which fly ash accounts for 80 to 85% [15]. Despite being used as a fine additive in the concrete industry, the utilization rate of fly ash remains low. For SCC, the replacement ratio of cement with fly ash is still relatively small, ranging from 15% to 25% by weight. This results in the unnecessary cost of managing excess fly ash from thermal power plants. Currently, there is no research on the use of high-volume fly ash of over 50 percent in SCC for construction projects in Vietnam. Therefore, a study on the workability, compressive strength, and chloride ion permeability of SCC containing a high volume of fly ash is necessary for its application.

This study focuses on investigating the impact of high-volume fly ash on the workability, compressive strength, and chloride ion permeability of SCC by replacing a portion of cement with different proportions (s) of fly ash. The replacement ratios of fly ash are 50% and 60%, respectively, by volume. The W/P ratio in the studied mixtures is 0.3 and 0.35, respectively. The SCC's workability is evaluated immediately after the completion of the mixing process. Compressive strength and chloride ion permeability are assessed at the ages of 7 days, 28 days, and 90 days respectively.

2. SIGNIFICANCE OF THE STUDY

This research focuses on the influence of high fly ash content on the essential properties of SCC at different ages. Specifically, six SCC mixtures were utilized, with fly ash replacement levels of 0%, 50%, and 60%, while the water-to-powder (W/B) ratio was set at 0.3 and 0.35. The study aimed to assess the workability, compressive strength, and chloride ion permeability of SCC at 7 days, 28 days, and 90 days.

The experimental findings shed light on the critical characteristics when using SCC with a high fly ash content, in particular, workability, compressive strength, and chloride ion resistance of SCC. These results will significantly contribute to enhancing the dissemination and effectiveness of utilizing SCC with a high fly ash content in construction projects in Vietnam.

3. EXPERIMENTAL METHODS, MATERIALS, AND MIX PROPORTIONS

3.1 Experimental Methods

a) Evaluation of SCC workability: The workability of SCC mixtures was assessed using various tests, including Slump Flow (SF), T500, J-ring, L-box, V-funnel, and the Sieve Segregation Ratio (Sr), following the guidelines of TCVN 12209:2018 [16].

b) Specimen preparation and determination of compressive strength: Concrete samples were taken, cast, and cured according to TCVN 3105:2022 [17]. The compression strength specimens had dimensions of 10x10x10cm. The samples were cast and initially cured under standard conditions, followed by immersion in water on the second day. The compressive strength testing was conducted following TCVN 3118:2022 [18].

c) Chloride ion permeability test (RCPT): Chloride ion permeability was evaluated using the Rapid Chloride Permeability Test (RCPT) method, as per TCVN 9337:2012 [19]. The test was conducted by applying a direct current through a cylindrical specimen with a diameter of 100mm and a height of 50mm. One face of the specimen was in contact with a 3% NaCl solution connected to the negative electrode, while the other face was in contact with a NaOH solution connected to the positive electrode. The chloride ion permeability through the concrete was assessed by measuring the charge passed through the specimen over a period of 6 hours.

3.2 Materials Used

The materials used in the experiments included: Vincem But Son PC40 cement; Yellow River sand with a modulus of 2.76; Crushed stone with Dmax=10mm, having a specific gravity of 2.75g/cm3; Fly ash: Pha Lai thermal power plant fly ash, F type according to ASTM C618; Superplasticizer admixture: MC-PowerFlow 5298, a new generation superplasticizer with improved polymer base, density of 1.05, conforming to ASTM C-494 Type G; Viscosity modifying admixture (VMA): CuLminal MHPC400, used as a viscosity-modifying agent.

3.3 Experimental Concrete Mix Proportions

The mix design of SCC was carried out using the method proposed by the Japan Society of Civil Engineers (JSCE) [20]. In the experiment, a total of 6 different mix proportions were used for evaluation. These mix proportions were created by varying the water-to-powder (W/P) ratio while keeping the volume of paste, aggregate, and sand constant. Specifically, W/P ratios of 0.3 and 0.35 were used, and the fly ash replacement levels were 0%, 50%, and 60%. The detailed mix proportions of SCC are shown in Table 1.

Table 1 Mix proportions of SCC

Mixture	W/P	Cement (kg)	Fly ash (kg)	Sand (kg)	Stone (kg)	Superplasticizer (kg)	VMA (kg)	Water (kg)
CP1	0.30	655.2	0.0	748.8	770	6.51	0.15	196.6
CP2	0.30	303.4	303.4	748.8	770	3.22	0.21	182.0
CP3	0.30	239.2	358.8	748.8	770	2.41	0.21	179.4
CP4	0.35	606.5	0.0	748.8	770	6.15	0.16	212.3
CP5	0.35	282.4	282.4	748.8	770	2.97	0.20	197.7
CP6	0.35	222.8	334.3	748.8	770	2.39	0.19	195.0

Table 2 Results of Workability Testing According to European Guidelines [21]

Mixture	SF (mm)	T_{500} (s)	V_{funnel} (s)	L_{box}	J_{ring} (mm)	Sr (%)
CP 1	665	4.70	11.8	0.81	9.9	5.4
CP 2	697	3.95	11.5	0.87	9.5	6.9
CP 3	707	3.67	11.2	0.90	9.3	7.05
CP 4	681	4.50	11.7	0.83	9.7	5.6
CP 5	730	3.37	11.1	0.91	9.1	7.1
CP 6	735	3.25	10.6	0.92	8.7	7.3

4. EXPERIMENT RESULTS

4.1 SCC Workability Test

According to [21], the values of slump flow (SF) ranged from 650mm to 800mm, T500 time from 2 to 5 seconds, J-ring value from 0 to 10mm, V-funnel time from 6 to 12 seconds, and segregation resistance (Sr) from 5% to 15%. The experimental results for slump flow (SF), T500 time, J-ring, L-box, V-funnel, and segregation resistance (Sr) are presented in Table 2. The slump flow values of the different concrete mixtures in the experiment varied from 665mm to 735mm. All mixtures exhibited T500 times between 3.25 seconds and 4.70 seconds, and V-funnel times between 10.6 seconds and 11.8 seconds. The mixtures passed the L-box test with flow ratios ranging from 0.81 to 0.92 and J-ring values from 8.7 to 9.9mm. All mixtures showed excellent flowability without any blockages. The segregation resistance of the mixtures ranged from 5.4% to 7.3%. Visual observations of the concrete rings, following the VSI guidelines of ASTM standard [22], based on the aggregate distribution, demonstrated the uniformity and good aggregate dispersion of the SCC mixtures (Figure 1). The experimental results indicated that increasing the fly ash content positively affected the slump flow of the SCC mixtures. When using 50% and 60% fly ash replacement, the slump flow increased by 4.8% and 6.3% respectively compared to the mixture without fly ash at an W/P ratio of 0.3, and by 7.1% and 7.9% respectively compared to the mixture without fly ash at an W/P ratio of 0.35. Additionally, an increase in fly ash content resulted in reduced viscosity of the SCC mixtures, as evidenced by decreased T500 and V-funnel times.

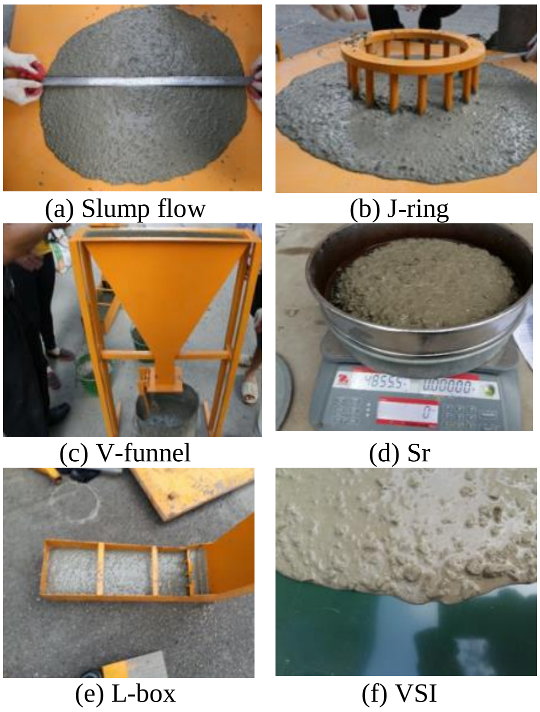

Fig.1 Workability Test Experiment of Self-Compacting Concrete

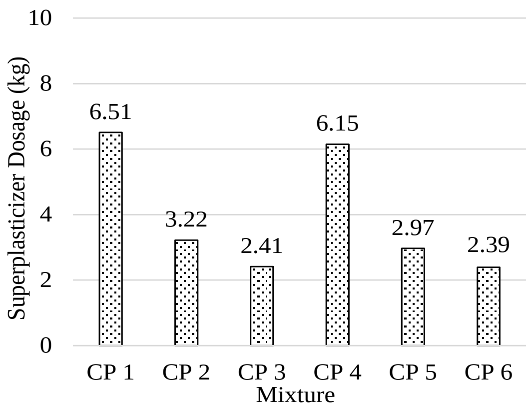

Fig.2 Superplasticizer Dosage in Different SCC Mixture

Furthermore, when using 50% and 60% fly ash, the segregation resistance of the mixtures tended to increase compared to the mixture without fly ash, with an increase of 27.96% and 30.5% respectively at an W/P ratio of 0.3, and 26.7% and 30.3% at an W/P ratio of 0.35. Nevertheless, the use of VMA admixture ensured a high stability of the mixtures with a high fly ash content, as evidenced by their good flow through the L-box and J-ring (Figure 1). For SCC mixtures without fly ash as a fine admixture, a significantly higher superplasticizer dosage was required to meet the workability requirements compared to the mixtures using fly ash as a fine admixture (Figure 2).

4.2 Experimental Results - Compressive Strength and Chloride Ion Permeability

4.2.1 Compressive Strength

The experimental results showed that the addition of fly ash reduced the compressive strength of SCC. For an W/P ratio of 0.3, the compressive strength of mixtures with 0%, 50%, and 60% fly ash replacements at ages of 7 days were 52.8 MPa, 28 MPa, and 24.3 MPa, respectively. At ages of 28 days, the corresponding values were 63.3 MPa, 50 MPa, and 44 MPa respectively, and at ages of 90 days, they were 66.4 MPa, 61.7 MPa, and 54.8 MPa respectively. The substitution of 50% and 60% fly ash reduced the compressive strength of SCC compared to the mixture without fly ash at the 7th day of age by 46.97% and 53.98% respectively, at the 28th day of age by 21.01% and 30.49% respectively, and at the 90th day of age by 7.17% and 17.55%, respectively (Figure 4).

Fig.3 The compression test of concrete samples

The compressive strength was also inversely proportional to the W/P ratio. Mixtures with an W/P ratio of 0.35 exhibited significantly lower compressive strength compared to mixtures with an W/P ratio of 0.3. For an W/P ratio of 0.35, the compressive strength of SCC with 0%, 50%, and 60% fly ash replacements at the age of 7 days were 48.1 MPa, 23 MPa, and 21 MPa, respectively. At the age of 28 days, the corresponding values were 57.9 MPa, 46.4 MPa, and 41.7 MPa, and at the age of 90 days, they were 61.4 MPa, 56.7 MPa, and 51.3 MPa. Thus, substituting 50% and 60% fly ash both resulted in a significant decrease in compressive strength compared to the control mixtures by 52.18% and 56.34% respectively at 7 days, 19.86% and 27.98% respectively at 28 days, and 7.65% and 16.45% at 90 days, respectively (Figure 5).

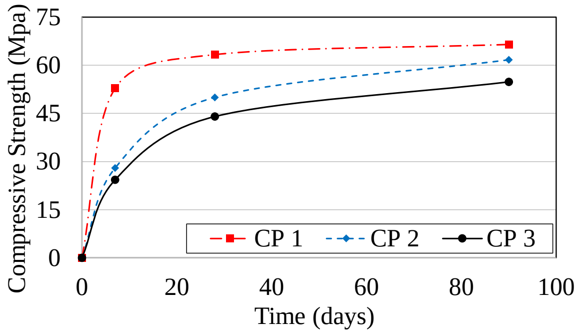

Fig.4 Compressive strength results of various mix designs with a W/P ratio of 0.3

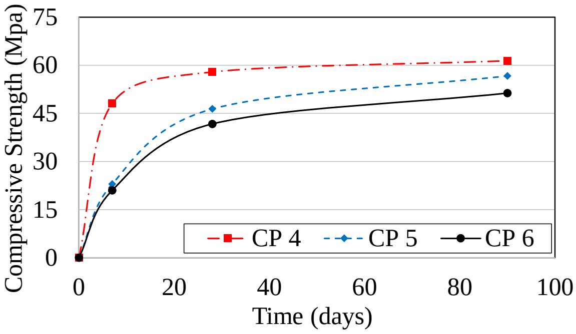

Fig.5 Compressive strength results of various mix designs with a W/P ratio of 0.35

At the early age of 7 days, due to the slow hydration reaction of fly ash, compressive strength values of mixtures using fly ash are significantly lower compared to that of the mixture without fly ash, ranging from 46.97% to 53.98%. Extended curing had a positive effect on the compressive strength development of SCC using fly ash as a fine admixture. The compressive strength of SCC at 90 days for mixtures with 50% and 60% fly ash replacements increased by 23.4% and 24.5% compared to 28 days at an W/P ratio of 0.3, and by 22.2% and 23.1% at an W/P ratio of 0.35. Meanwhile, mixtures without fly ash showed relatively little development of compressive strength with extended curing, increasing by only about 5-6% compared to 28 days. This can be explained by the low early-age reactivity of fly ash.

The continuous curing process accelerated the formation of secondary hydration products of fly ash and filled the voids of SCC, thereby increasing the strength [23].

However, due to the high fly ash content, the amount of calcium hydroxide produced from the hydration reaction of cement was insufficient to react with fly ash, so part of the fly ash acted as inert material, resulting in significantly lower compressive strength of mixtures with high fly ash content compared to the control samples.

4.2.2 Chloride Ion Permeability

The experimental results at 7 days showed that the charge passed through the concrete samples with 0%, 50%, and 60% fly ash replacements at an W/P ratio of 0.3 were 5970 C, 3917 C, and 3810 C respectively. At an W/P ratio of 0.35, the corresponding values were 6142 C, 4096 C, and 3910 C respectively. The charge value ranges from 2000 C to 4000 C and >4000C, indicating a moderate to high chloride permeability level according to TCVN 9337:2012. The results showed that there is a big difference in charges passed between mixtures with fly ash and without fly ash at the same W/P ratio. Increasing the fly ash content for mixtures at both W/P ratios resulted in a decrease in the charge by approximately 33.20% to 36.34%. This is because fly ashes have the ability to absorb and bind chloride ions stronger than ciment particles do. Simultaneous, when the W/P ratio increased from 0.3 to 0.35, the charge passed for mixtures with 0%, 50%, and 60% fly ash increased by 9.09%, 7.30%, and 5.96% respectively. This result indicates that the permeability of SCC depends on the W/P ratio as well. As the W/P ratio increases, the concrete's void content also increases, leading to higher permeability (Figure 6, 7).

Fig.5 The experiment for measuring chloride ion permeability through concrete

However, at 28 days, the charge passed through mixtures with fly ash was significantly lower than that of mixtures without fly ash. Mixtures without fly ash had a charge passed of 2556 C and 2751 C at an W/P ratio of 0.3 and 0.35, respectively, indicating a moderate permeability according to TCVN 9337:2012. In contrast, mixtures with 50% and 60% fly ash replacements had a charge passed of 446 C, 416 C at an W/P ratio of 0.3 and 771 C, 684 C at an W/P ratio of 0.35, indicating very low permeability. The experimental results also showed that mixtures with 60% fly ash had a greater reduction in permeability compared to mixtures with 50% fly ash. Specifically, for an W/P ratio of 0.3, the permeability of mixtures with 50% and 60% fly ash was reduced by 82.55% and 83.72% respectively compared to mixtures without fly ash. For an W/P ratio of 0.35, the reductions were 71.97% and 75.14% respectively (Figure 6, 7). Moreover, the extended curing time was beneficial in reducing chloride ion ingress for mixtures with high fly ash content. When the curing time increased from 28 days to 90 days, the charge passed for mixtures with 50% and 60% fly ash decreased by 67.04% and 68.51% respectively at an W/P ratio of 0.35, and 77.43% and 77.92% respectively at an W/P ratio of 0.35.

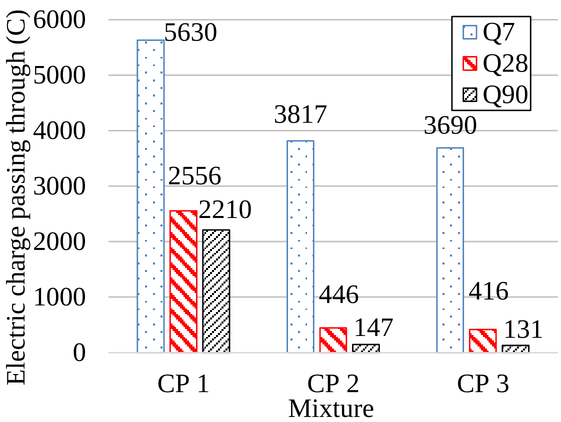

Fig.6 Permeability results for different mix proportions with W/P of 0.3

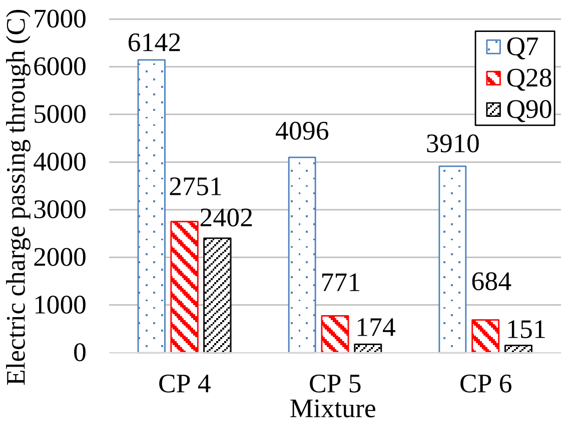

Fig.7 Permeability results for different mix proportions with W/P of 0.35

Meanwhile, mixtures without fly ash had a smaller reduction in the charge passed with extended curing; the reductions for mixtures at W/P ratios of 0.3 and 0.35 were 13.54% and 12.69%, respectively. This was because the pozzolanic reaction of fly ash was slower than the hydration reaction of cement. The pozzolanic reactions of fly ash produced secondary hydration products that filled the voids and formed a dense structure for SCC. The reduction in void volume increased the impermeability (reduced permeability) of mixtures containing fly ash compared to mixtures without fly ash. Furthermore, fly ash particles have a higher ability to adsorb and bind chloride ions than cement particles [10], which further reduces the chloride ion ingress.

5. CONCLUSIONS

The research results show that high-quality Class F fly ash can be used to produce SCC with excellent workability, meeting the European guidelines. Increasing the fly ash content enhances the workability of SCC significantly and reduces the need for superplasticizer additives.

The compressive strength of SCC using 50% and 60% replacement of Class F fly ash at 28 days reaches values of 50 MPa and 44 MPa respectively with an W/P ratio of 0.3, and 46.4 MPa, 41.7 MPa respectively with an W/P ratio of 0.35. Moreover, by extending the curing time to 90 days, the compressive strength of SCC using 50% and 60% fly ash increases by 22.2-24.5% compared to that of SCC at 28 days.

The chloride ion permeability of SCC using 50% and 60% fly ash at early ages (7 days) increases by about 33.20 to 36.34% compared to the control sample without fly ash, depending on the W/P ratio. At later ages (28 days), the chloride ion permeability of SCC with 50% and 60% fly ash falls into the category of very low permeability and decreases compared to the control sample without fly ash by 82.55% and 83.72% respectively with an W/P ratio of 0.3, or 71.97% and 75.14% respectively with an W/P ratio of 0.35. Prolonging the curing time to 90 days results in further reductions in chloride ion permeability for SCC using 50% and 60% fly ash, with reductions of 67.04% and 68.51% respectively for an W/P ratio of 0.3, or 77.43% and 77.92% respectively for an W/P ratio of 0.35.

The use of high-content Class F fly ash in SCC production offers significant advantages. It allows for the creation of SCC with relatively high compressive strength and very low chloride ion permeability. In addition, substituting a high-content fly ash for cement not only helps reduce the production cost of SCC but also has positive environmental benefits. The application of this type of concrete is an ideal choice for structures that frequently encounter aggressive factors causing corrosion of steel reinforcement in Vietnam, such as coastal projects, hydraulic structures or transportation infrastructure.

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