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Research and development of high performance fine-grained concrete for floating pontoons

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KEYWORDS

Floating pontoon
High performance fine grained concrete
High strength
Water impermeability
Chloride ion resistance

ABSTRACT

The paper presents the results of research and development of high-performance fine-grained concrete (HPFGC) for floating pontoons. Concrete Pontons have thin-walled structures and often work in water and seawater environments. The developed HPFGC has high flowability and can self-compact into the formwork, suitable for the construction of thin-walled structures such as floating pontoons. The amount of Silicafume used is from 0 - 15%, the amount of fly ash used is from 0 - 30% replacing the amount of cement used in HPFGC. The experimental research results show that it is possible to manufacture HPFGC using fly ash/silicafume with a compressive strength of 60 - 80 MPa. This HPFGC has high water impermeability and chloride ion resistance, suitable for floating pontoons working in water environments, including seawater environments.

1. Introduction

Floating structures that are large-scale are majorly classified as either pontoons or semisubmersibles. Pontoons are basically floating slabs with low depth-to-width ratios that are placed in calm seas along the shore, inside a cove or lagoon, or where breakwaters and other protective structures may be built to shield the structure from high waves and surges [1]. Moreover, in the history of floating structures, a prominent position is also enjoyed by the floating bridges. Floating walkways are a linear pontoon system formed from numerous hinged flotation modules and supported by a boat ramp lane during tides.

The concept of concrete pontoons revolves around harnessing the inherent strength and buoyant quality of concrete to create versatile platforms that enhance maritime infrastructure. By utilizing this durable material, engineers and architects can design pontoons that serve as the foundation for a wide range of applications, from recreational facilities to critical transportation hubs. Concrete pontoons are a proof of innovation in maritime engineering, offering sustainable, reliable and resilient solutions for waterfront development and utilization.

The use of locally available materials as well as the use of industrial and agricultural waste in building industry has become a potential solution to the economic and environmental problems of particularly developing countries. Coarse aggregate is considered as the main ingredient to produce Portland cement concrete. However, the resources of this material are depleting in many countries or in specific regions, thereforefinding a potential substitute for coarse aggregate is crucial. The use of sand (natural or crushed) as a substitute for coarse aggregate to produce sand concrete was investigated. This kind of concrete has strength comparable with conventional Portland cement concrete. By definition, sand concrete is therefore defined as a fine aggregate concrete,in which coarse aggregate is replaced by sand and fine aggregate is by filler material [2-4]. High performance fine-grained concrete (HPFGC) is considered as a new generation of sand concrete, and can be comparablewith high performance concrete in strength and durability.

FA is commonly used to produce high flowability concrete, i.e. SCC/SCHPC. The addition of FA increases workability and the long-term compressive strength of concrete. Concrete containing FA needs less SP to obtain a similar slump flow compared with concrete containing only cement as binder, due to its spherical particles and lower water demand compared to cement [5-9]. The partial cement replacement by FA can significantly improve rheological properties of flowing concrete and of high flowability concrete SCC/SCHPC [10, 11]. SF is a main ingredient of HPC due to its exceptional properties, i.e. the ultra-fine and spherically-shaped particles and the very high amorphous silica content of about 90 wt.%. The addition of SF to SCC/SCHPC increases yield stress and viscosity and thus significantly reduces slump flow, segregation and bleeding due to its high fineness [11-14]. Incorporating SF in concrete results in an increase in compressive strength, in the modulus of elasticity, and in the flexural strength, and improves durability even at early ages compared to other MAs [11, 14]. The performance of SCHPC is significantly improved by using SF, however it is expensive due to the limited availability especially in developing countries.

The objective of this study is to investigate effects of SF and FA on workability, compressive strength, water absorption, water impermeability and chloride ion resistance of HPFGC. These properties were specified for producing floating pontoons working in water environments, including seawater environments.

2. Experimental program

2.1. Materials

Portland cement (PC40 conforming to Vietnamese standard

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TCVN 2682:1999), Fly ash (FA), Silicafume (SF) and two kinds of natural dune sand, i.e. fine sand and coarse sand, were used in this study. The physical properties and the chemical composition of the cement, FA, and SF are summarized in Table 1. The physical properties of fine and coarse sand are presented in Table 2. In addition, a polycarboxylate-based superplasticizer (SP) was used.

Table 1. Chemical composition and physical properties of cement and mineral admixtures.

Chemical analyses (%)	PC40	SF	FA
SiO_2	21.29	96.2	59.5
Al_2O_3	5.72	0.70	24.48
Fe_2O_3	3.30	0.30	5.74
CaO	63.18	0.00	0.84
MgO	1.10	0.10	1.6
Na_2O	0.12	0.06	0.17
K_2O	0.30	0.37	3.17
L.O.I	0.193	1.6	2.62
Density (g/cm^3)	3.10	2.26	2.26
Mean particle size (μm)	16.12	0.29	16.39
Blaine SSA[BET-SSA] (m^2/g)	0.369	[26.43]	[2.14]

L.O.I: Loss on ignition

Table 2. Sieve analysis and physical properties of the fine and coarse sand.

Sieve size (mm)	Cumulative residue (%)	
	Fine sand	Coarse sand
5.0	0.0	1.3
2.5	0.0	28.7
1.25	0.1	57.6
0.63	0.2	73.1
0.315	6.5	90.6
0.15	97.2	97.9
Fineness modulus	1.04	3.48
Density (g/cm^3)	2.65	2.65
Absorption (%)	2.1	1.9

2.2. *Mixture proportions*

The constituent materials of HPFGC mixtures were calculated using the absolute volume method. The packing theory of Funk and Dinger [15] with the exponent q = 0.25 was adopted to determine the grading of aggregate, according to the following equation. The primary paste volume for filling ability was computed on the basis of the void content of compacted aggregate. The SP dosage for the concrete was set on the basis of its SSD.

$$P(D) = \frac{D^q - D_{\min}^q}{D_{\max}^q - D_{\min}^q}$$

Where,

- P(D) – the percentage by mass of aggregate passing through a sieve with a size of D, mm;

- Dmin and Dmax – the smallest and largest particle sizes in the aggregate mixture, mm.

The proportioning of different types of aggregates will result in a particle size distribution of the aggregate mixture that matches the theoretical curve with the smallest standard deviation. In this study, the Funk and Dinger packing density theory is applied with q = 0.25, Dmax = 5.0 mm, and Dmin = 0.075 mm. The particle size distribution curves of the aggregate mixture with different fine sand/coarse sand ratios are shown in Fig 1. It can be observed that the fine sand/coarse sand ratio of 30/70 provides the aggregate mixture that best fits the theoretical curve. Therefore, the fine sand/coarse sand ratio of 30/70 is selected for the calculation of the fine-grained concrete mixture proportions.

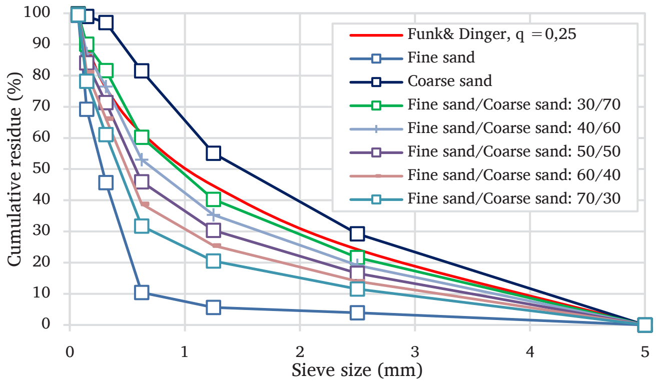

Fig 1. Particle size distribution of aggregate.

Table 3. Mixture proportions of HPFGC investigated.

Mixture	Cement (kg/m^3)	FA (kg/m^3)	SF (kg/m^3)	SP (kg/m^3)	Water (kg/m^3)	Fine sand (kg/m^3)	Coarse sand (kg/m^3)
100PC	666	0	0	10,0	226	450	1050
90PC.10FA	599	67	0	9,0	226	450	1050
80PC.20FA	533	133	0	7,3	226	450	1050
70PC.30FA	466	200	0	5,0	226	450	1050
95PC.5SF	633	0	33	13,3	226	450	1050
90PC.10SF	599	0	67	15,0	226	450	1050
85PC.15SF	566	0	100	16,7	226	450	1050

2.3. Experimental methods

In this study, standard testing methods were used to determine the physical and mechanical properties of the materials and the properties of HPFGC. The standard testing methods include: TCVN 141: 2008, Cement - Methods for chemical analysis; TCVN 8262: 2009, Fly ash - Methods for chemical analysis; ASTM C136, Methods for sieve analysis of aggregates; ASTM C33, Test for particle size distribution of aggregates; ASTM C29, Determination of bulk density and voids in aggregates; ASTM C128, Determination of specific gravity and water absorption of aggregates; TCVN 3121-11: 2003, Mortar - Test methods, part 11: Determination of flexural and compressive strength of hardened mortar. Chloride penetration resistance was determined at 28 days in agreement with ASTM C1202. The tests were carried out in triplicate and the average values were reported.

Workability test of the concrete mixture: The workability of the fresh concrete is evaluated through the slump flow. The slump flow of fresh HPFGC is determined using the mini-cone method, with dimensions of a large base diameter of 100 mm ± 0.5 mm, a small base diameter of 70 mm ± 0.5 mm, and a height of 60 mm ± 0.5 mm. The slump flow of fresh HPFGC is determined by measuring the average value of two perpendicular diameters.

The compressive strength test samples are 40x40x160 mm in size according to the standard. The compressive strength of HPFGC samples is determined at the ages of 3, 7, and 28 days.

Mixing procedure: All mixtures were prepared in a compulsory mixer (5 liters) at 140 rpm with total mixing time of 10 minutes. Coarse and fine sand and powder materials (cement, FA/SF.) were mixed in dry conditions for a period of 2 minutes. Next, about 80 % of the water was added whereupon the concrete mixture was mixed for 2 minutes. Finally, about 20 % of the water and superplasticizer were added and the concrete mixture was mixed for 6 minutes.

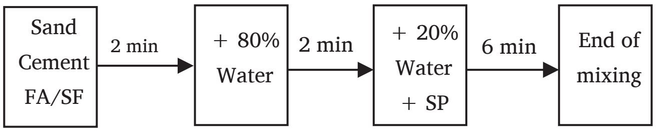

Fig 2. Mixing procedure for HPFGC .

3. Results and discussion

3.1. Workability of fresh HPFGC

The workability of fresh HPFGC is an important property that affects the construction and compaction process of the concrete mixture. Unlike conventional concrete, since the primary purpose is to use HPFGC to create thin structures or areas with dense reinforcement, such as thin-walled reinforced concrete structures for pontoons, the concrete mixture requires high flowability and uniformity to facilitate the construction process.

The workability testing method for this concrete differs from traditional concrete as it does not use large aggregates but shares similarities with the method used for determining the workability of mortar. Therefore, in this study, the workability of the concrete mixture was determined based on the standard mortar cone slump flowtest

3.1.1. Effect of fly ash on workability of fresh concrete

The workability of the fresh concrete using fly ash is presented in Fig 3. The workability of the fresh concrete is evaluated through the slump flow. The slump flow of HPFGC mixture is tested using the mini-cone method.

The test results show that as the fly ash content increases, the workability of the concrete mixture improves. Specifically, for mixtures using 0%, 10%, 20%, and 30% fly ash, the slump flow of the concrete mixture is 285 mm, 290 mm, 300 mm, and 310 mm, respectively. This result is consistent with previous studies. Fly ash has a spherical particle shape, which creates a "ball bearing effect," reducing friction between aggregate particles and thus improving workability [16].

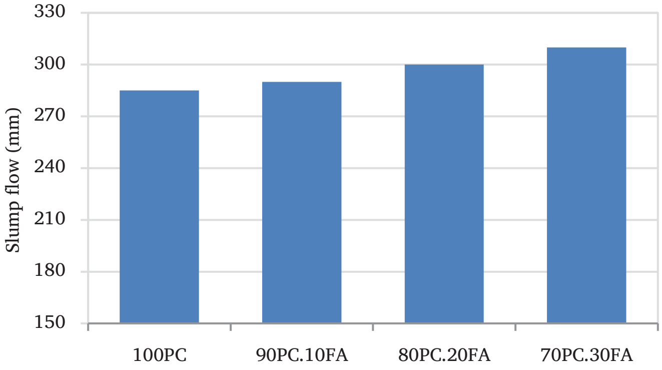

Fig 3. Effect of fly ash on workability of fresh concrete.

3.1.2. Effect of silicafume on workability of fresh concrete

The workability of the concrete mixture using silica fume is presented in **Fig 4**. The workability of the concrete mixture is evaluated through the flow spread. The slump flow of HPFGC mixture is tested using the mini-cone method.

The test results show that as the silica fume content increases, the workability of the concrete mixture decreases. For mixtures using 0%, 5%, 10%, and 15% silica fume, the slump flowof the concrete mixture is 285 mm, 285 mm, 280 mm, and 270 mm, respectively. This result is consistent with previous studies [17]. Silica fume has spherical particles; however, because the particle size is very small, over 100 times smaller than cement particles, it leads to a significantly larger surface area, which requires more water. As the amount of silica fume replacing cement increases, the available lubricating water decreases, leading to increased friction between solid particles and thus reducing the slump flow (workability) of the concrete mixture.

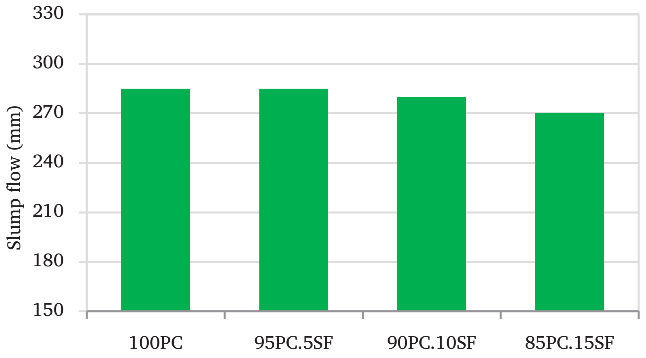

Fig 4. Effect of silicafume on workability of fresh concrete.

3.2. Compressive Strength of HPFGC

3.2.1. Effect of fly ash on compressive strength of concrete

The compressive strength of fly ash concrete is presented in Fig 5 and Fig 6. It can be seen that the compressive strength of the concrete decreases as the amount of fly ash used increases. Concrete using 100% cement achieves the highest compressive strength of 78.2 MPa at 28 days. When replacing cement with fly ash at rates of 0%, 10%, 20%, and 30% by mass, the compressive strength at 28 days for HPFGC is 74.6 MPa, 73.3 MPa, and 68.8 MPa, respectively.

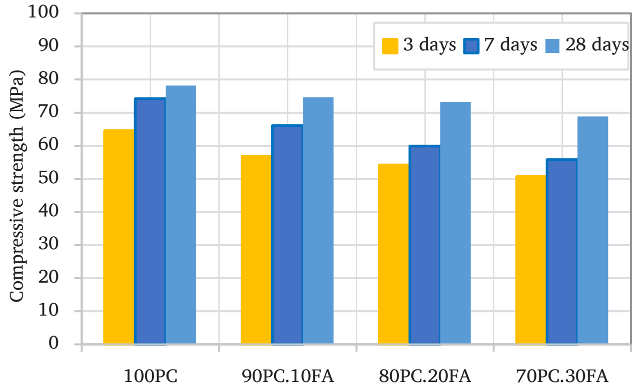

Fig 5. Effect of fly ash on compressive strength of concrete.

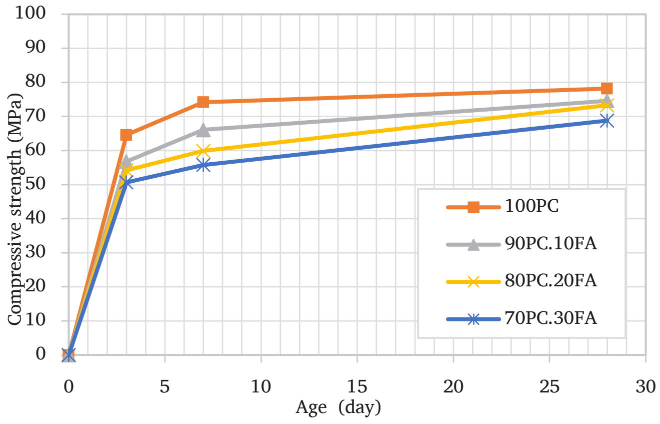

Fig 6. Development of Compressive strength of concrete containing fly ash.

The compressive strength decreases because the reactivity of fly ash is lower than that of cement, and fly ash typically tends to develop strength at later ages (90, 180, 360 days). This result is entirely consistent with previous studies on the effect of fly ash on the strength development of concrete [16].

3.2.2. Effect of silicafume on compressive strength of concrete

The compressive strength of silicafume concrete is presented in Fig 7 and Fig 8. It can be observed that the compressive strength of the concrete increases as the amount of silica fume replacing cement increases. The concrete using 100% cement achieves the lowest compressive strength of 78.2 MPa at 28 days. When replacing cement with SF at rates of 5%, 10%, and 15% by mass, the compressive strength at 28 days for HPFGC increases to 84.6 MPa, 85.8 MPa, and 68.8 MPa, respectively.

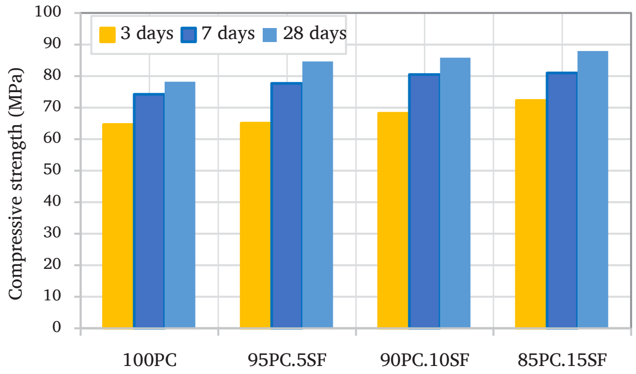

Fig 7. Effect of silicafume on compressive strength of concrete.

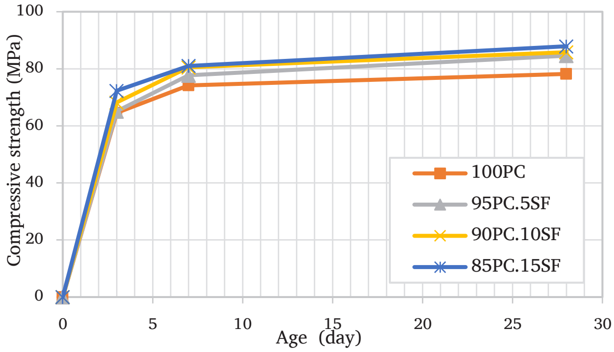

Fig 8. Development of Compressive strength of concrete containing silicafume

3.3. Water absorption and water resistance of HPFGC

3.3.1. Effect of fly ash on water absorption and water resistance of HPFGC

The water impermeability is assessed through the maximum pressure at which the sample does not allow water to penetrate. The water absorption and impermeability of the concrete using fly ash are presented in Fig 9, and Fig 10. Increasing the fly ash content does not significantly affect the water impermeability and only slightly increases the water absorption of the concrete.

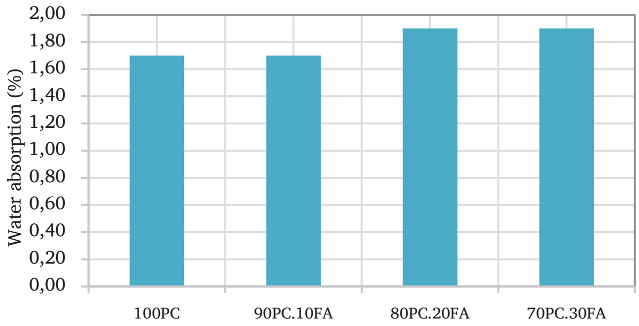

Fig 9. Effect of fly ash on water absorption of concrete.

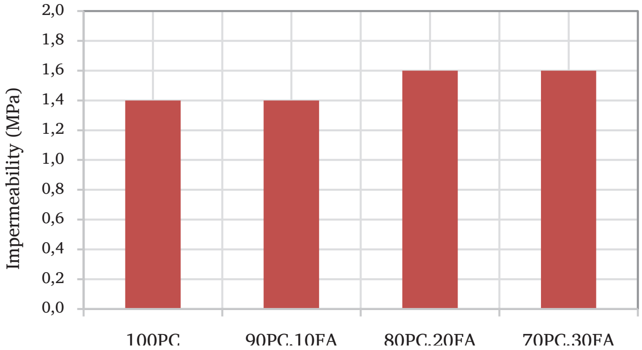

Fig 10. Effect of fly ash on water impermeability of concrete.

3.3.2. Effect of silicafume on water absorption and water resistance of HPFGC

Water impermeability is assessed through the maximum pressure at which the sample does not allow water to penetrate. The water absorption and impermeability of the concrete using silica fume are presented in Fig 11 and Fig 12. Increasing the silica fume content does not significantly affect the water impermeability and slightly reduces the water absorption of the concrete.

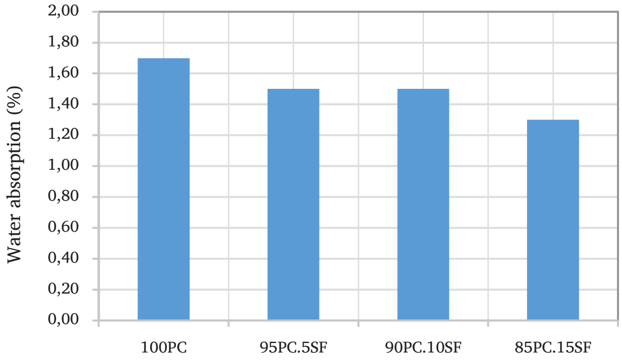

Fig 11. Effect of silicafume on water absorption of concrete.

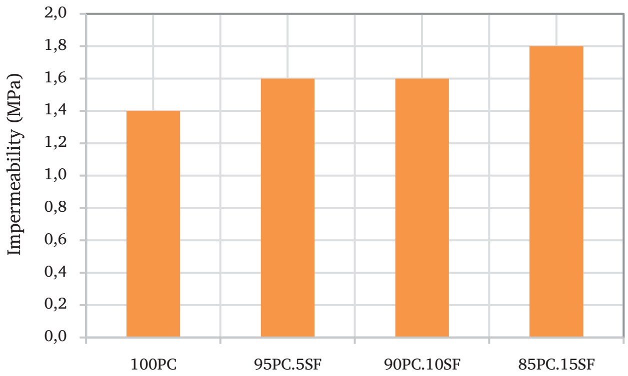

Fig 12. Effect of silicafume on water impermeability of concrete.

3.4. Chloride penetration resistance of HPFGC

3.4.1. Effect of fly ash on Chloride penetration resistance

The experimental results measuring the chloride ion permeability of HPFGC using fly ash are presented in Fig 13. In this study, fly ash replaces cement at rates of 10%, 20%, and 30% by mass.

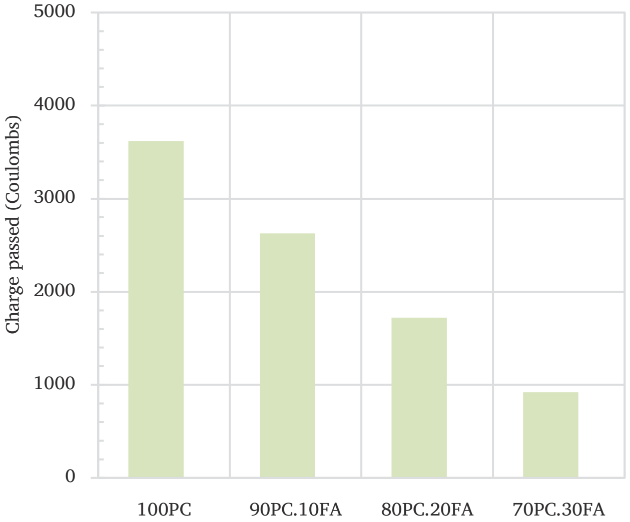

Fig 13. Effect of fly ash on Chloride penetration resistance of concrete.

The charge passed through the samples using 10%, 20%, and 30% fly ash replacing cement is 2628, 1721, and 921 Coulombs, respectively, which is significantly lower than that of the control sample (100% cement) with a charge of 3620 Coulombs. Increasing the amount of fly ash reduces the charge passed through HPFGC, indicating improved chloride ion impermeability.

Using fly ash can enhance the chloride ion permeability of HPFGC because the ultra-fine particle size of fly ash fills the small pores in the concrete. Furthermore, the pozzolanic effect of fly ash generates CSH, which helps increase the density of the concrete, thereby improving its impermeability [16, 18].

3.4.2. Effect of silicafume on Chloride penetration resistance

The chloride ion penetration of concrete using silica fume is presented in Fig 14. In this study, silica fume replaces cement at rates of 5%, 10%, and 15% by mass. Increasing the silica fume content reduces the chloride ion penetration and decreases the permeability of HPFGC.

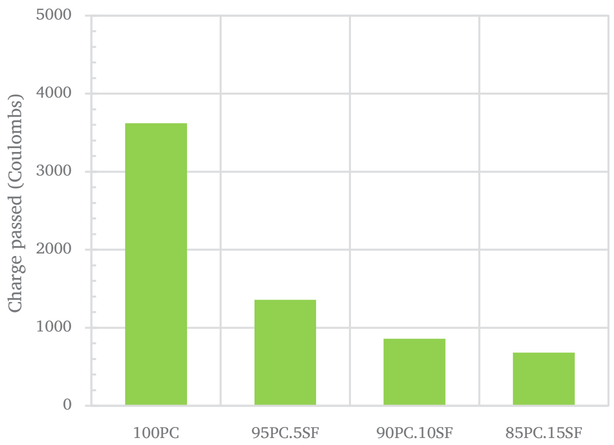

Fig 14. Effect of silicafume on Chloride penetration resistance concrete.

The charge passed through the samples using 5%, 10%, and 15% silica fume is 1359.4, 860.1, and 680.9 Coulombs, respectively, which is significantly lower than that of the control sample (100% cement) with a charge of 3620 Coulombs. Increasing the silica fume content reduces the chloride ion penetration, especially in samples using 10-15% silica fume, which exhibit very low permeability (charge passed through the sample < 1000 Coulombs). The use of silica fume significantly improves the chloride penetration resistance of HPFGC, which can be explained by the ultra-fine particle size of silica fume filling the small pores in the concrete. Additionally, with a high content of amorphous SiO2, the pozzolanic effect is substantial, generating CSH that helps increase the density of the concrete.

4. Conclusions

Based on the experimental results in the present study, the following conclusions can be drawn.

- Fly ash can be used to produce HPFGC with good workability (slump flow from 290-310 mm), achieving compressive strength of 60-70 MPa at 28 days.
- Silica fume can be used to produce HPFGC with good workability (slump flowfrom 270-285 mm), achieving compressive strength of 80-90 MPa at 28 days.
- Using 10-30% fly ash to replace cement increases the water impermeability and water absorption of HPFGC.
- Using 5-15% silica fume to replace cement increases the water impermeability and decreases the water absorption of HPFGC
- Using 10-30% fly ash to replace cement significantly reduces the chloride ion penetration of HPFGC. Increasing the fly ash content decreases the chloride ion penetration of HPFGC, and with 30% fly ash, the concrete has a very low chloride ion penetration of nearly 1000 Coulombs.
- Using 5-15% silica fume to replace cement greatly reduces the chloride ion penetration of HPFGC. Increasing the silica fume content decreases the chloride ion penetration of HPFGC, and with 10-15% silica fume, the concrete exhibits very low permeability of over 1000 Coulombs.

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