JOURNAL OF MATERIALS & CONSTRUCTION

Journal of Materials and Construction
ISSN 2734-9438
Website: www. jomc.vn

High -volume fly ash self-compacting concrete for coastal constructions: A sustainable development solution

Nguyen Hung Cuong[1*]

[1] Faculty of Building and Industrial Construction, Hanoi University of Civil Engineering

KEYWORDS

Self-compacting concrete
Workability
Compressive strength
Chloride ion permeability
Water absorption
High volume fly ash

ABSTRACT

This article presents the research results on the effectiveness of applying high-volume fly ash self-compacting concrete (SCC) in constructing environmentally influenced structures along the coast of Vietnam. SCC is designed with fly ash replacing 70% and 80% of cement. Technical criteria evaluated include workability, compressive strength, chloride ion permeability, water absorption, and dry bulk density of SCC. Additionally, the energy consumption, environmental emissions, and production costs of high-volume fly ash SCC are also assessed. The results show that SCC with 70% and 80% fly ash replacement by weight meets construction requirements, with compressive strengths at 28 days reaching 25.1 MPa and 21.2 MPa, and at 90 days reaching 49.4 MPa and 28.3 MPa respectively; chloride ion permeability is very low, electrical resistivity at 28 days is 690C and 539C; water absorption at 28 days is approximately 2.3% and 2.6%; dry bulk density at 28 days is 2239 kg/m^3 and 2225 kg/m^3. Compared to conventional concrete with equivalent compressive strengths of 20 MPa and 25 MPa (BT200, BT250), using high-volume fly ash SCC with 70% and 80% fly ash replacement results in energy consumption reduction by 45.28% and 53.45% respectively; CO_2, NO_x, SO_x emissions are reduced by (52.41%, 54.26%, 53.95%) and (62.21%, 64.33%, 64.13%); material production costs decrease by 15.14% and 17.16% respectively. Utilizing high-volume fly ash SCC as a solution for coastal constructions proves to be technically feasible, cost-effective, environmentally friendly, and sustainable.

1. Introduction

Vietnam is a coastal nation with a coastline stretching approximately 3.260 km, comprising numerous coastal and offshore islands. About 50 % of the population resides in 28 coastal provinces and cities [1]. Consequently, a significant number of constructions are erected in areas affected by the marine environment. Under the influence of the marine environment, the quality and longevity of structures are severely impacted. According to [2], over 50 % of concrete structural components in marine environments suffer corrosion and damage within 10 to 30 years of use. Corrosion and deterioration of concrete structures and reinforced concrete primarily occur due to several factors such as: the carbonation process corrodes the passive protective steel membrane (i), the interaction of SO_4^{2-} ions with cement hydrolysis products forms Ettringite minerals causing structure degradation (sulfate corrosion) (ii), and the diffusion of chloride ions and moisture into concrete under high air temperatures (iii) [2].

The marine environment is classified into submerged, tidal, atmosphere above the water surface, atmosphere near the coast (within 0-1km from the shoreline), and atmosphere close to the coast (1-30km from the shoreline) [3]. Depending on the degree of exposure to the marine environment, the requirements for reinforced concrete vary. For instance, for structures in the atmosphere above the coast, non-obstructive structures require a minimum concrete strength of 25MPa, waterproofing of 6atm, a protective concrete layer thickness of 5cm, and a crack width limit smaller than 0.1mm. However, in cases where the structure is required to last over 50 years, higher standards are necessary, such as increasing the concrete strength by an additional 10MPa and enhancing waterproofing by one level or employing corrosion-resistant steel coatings or waterproof coatings on the outer surface of concrete. This illustrates that for reinforced concrete structures built in coastal environments, ensuring the longevity of the structure significantly increases construction investment costs. Therefore, it is crucial to research suitable concrete materials with low costs and environmental friendliness to mitigate steel corrosion and concrete degradation.

Self-compacting concrete (SCC) is known for its characteristics of small voids, high durability, and excellent waterproofing [4]. The production process of SCC adheres to the principle of using active mineral additives, low water-to-powder ratio, minimizing the volume of coarse aggregates, and high volume of superplasticizers [5]. The material requirements for manufacturing SCC are quite similar to the material requirements for concrete in coastal environments according to TCVN 327:2004, such as using cement with low C_3A volume (less than 10 %), employing superplasticizers to reduce the water-to-cement ratio, and using mineral additives to reduce water permeability. In Vietnam, SCC has been effectively applied in many construction projects

---

*Corresponding author: cuongnh@huce.edu.vn

Received 17/04/2024, Revised 17/05/2024, Accepted 23/05/2024
Link DOI: https://doi.org/10.54772/jomc.v14i01.704

in highly corrosive environments, such as the T23-T17 culvert project in U Minh - Ca Mau and other projects within the saline-freshwater boundary system in Soc Trang - Bac Lieu province. These projects utilize SCC M350, with a waterproofing grade of W = 12 atm after 28 days. The application of SCC has saved 60-70 % of labor costs for casting, finishing, and reduced 50 % of concrete compaction and surface finishing costs, shortening the construction time by 1.2-1.5 times. However, the material cost of producing SCC is higher than that of traditional concrete by about 1.2-1.4 times [6].

Fly ash is a byproduct generated from the thermal power production process and is commonly used as a mineral additive in concrete manufacturing. Due to its low cost compared to cement, increasing the proportion of fly ash usage reduces concrete production costs. According to [7], the percentage of fly ash replacing cement is considered low if below 15 %, moderate if between 15-30 %, high if between 30-50 %, and very high if over 50 %. Research has shown several advantages of using fly ash as a mineral additive in concrete: it reduces the water demand of concrete, typically replacing 10 % of fly ash can reduce 3 % of the mixing water. Using fly ash improves the workability of the concrete mix, as well as enhances adhesion and reduces stratification. The spherical shape of fly ash particles makes the concrete mix easier to pump and reduces equipment wear [7]. Due to the reduced water demand when using fly ash, the mixing water volume decreases, resulting in concrete with a higher fly ash volume having lower shrinkage than traditional concrete [8, 9]. Additionally, studies have shown that fly ash-containing concrete significantly reduces chloride permeability over time [10, 11]. In a study by Naik [12] on concrete samples taken from concrete pavements with high fly ash volume at ages 7-14 years, the Rapid Chloride Permeability Test showed a reduction in chloride ion permeability with increasing fly ash volume. Moreover, concrete samples using high fly ash volume had chloride ion permeability at negligible levels [12]. Fly ash with low calcium oxide volume (Type F) has the ability to control harmful alkali-silicate reactions in concrete when replaced in a reasonable amount (20-30 %), while Type C fly ash with high calcium volume is ineffective in this regard [13]. Using Type F fly ash with low calcium oxide volume can enhance resistance to chemical attack when concrete is exposed to environments with high sulfate ion volume [14].

In Vietnam, research on the application of SCC with high fly ash volume for coastal structures is still limited. However, this type of concrete offers suitable properties for structures exposed to coastal environments. Therefore, this study focuses on investigating the use of SCC with high fly ash volume in the coastal area. The characteristics evaluated in the study include workability, compressive strength, chloride ion permeability, water absorption, energy consumption, environmental impact, and economic aspects. The fly ash volume used in the study is 70 % and 80 % relative to the weight of the cementitious material in the concrete mix.

2. Materials and mix proportions

2.1. Materials used

The materials used in the experiment include: Vicem But Son PC40 cement; river sand from the Red River with a fineness modulus of 2.76; stone with a maximum size (Dmax) of 10mm and a density of 2.75g/cm^3; fly ash from Phả Lại thermal power plant, type F according to TCVN 10302:2014 standard; a new generation of superplasticizer (Sp) BiFi-HV298, polymer-based, with a density of 1.05, compliant with ASTM C-494 type G standard; and a viscosity-modifying admixture (VMA) Culminal MHPC400.

2.2. Mix proportions for experimental concrete

The mix proportions of SCC were designed following the experimental method as guided [15]. This study utilized a total of three different mix proportions for evaluation. The mix proportions have a water-to-powder ratio (W/P) of 0.35, with fixed amounts of stone and sand. The fly ash volume, by weight, was 0 %, 70 %, and 80 % of the cementitious material. The dosage of superplasticizer was adjusted according to the workability requirements of the SCC mix. The detailed mix proportions for SCC are presented in Table 1.

Table 1. Material Proportions for 1m^3 of SCC.

Mixture	Cement (kg)	Fly ash (kg)	Sand (kg)	Stone (kg)	Sp (kg)	VMA (kg)	Water (kg)
CPF0	606.5	0.0	748.8	770	6.15	0.16	212.3
CPF70	164.9	384.7	748.8	770	5.49	0.21	192.4
CPF80	108.5	433.9	748.8	770	5.42	0.25	189.8

3. Experimental results and discussion

3.1. Workability testing of SCC mixes

The workability of SCC mixes was evaluated according to TCVN 12209:2018 [16] standard. The slump flow of CPF0, CPF70, and CPF80 mixes were 681mm, 740mm, and 742mm, respectively. The viscosity of SCC mixes was assessed through the T500/Vfunnel flow time, which were 4.5s/11.7s, 3.15s/9.7s, and 3.01s/9.1s, respectively. The passing ability through L-box/J-ring was observed to be 0.83/9.7mm, 0.93/8.6mm, and 0.95/8.5mm, respectively. The segregation degree Sr was found to be 5.6 %, 8.7 %, and 9.3 % for CPF0, CPF70, and CPF80 mixes, respectively. It can be observed that all three mix designs of SCC met the construction requirements specified by TCVN 12209:2018. The SCC mixes exhibited good workability, without segregation or bleeding during the J-ring, L-box, and V-funnel tests. The aggregates were evenly distributed across the ring and did not segregate or settle. Additionally, the incorporation of fly ash increased the flowability and passing ability of the SCC mixes. The slump flow of CPF70 and CPF80 mixes increased by 8.6 % and 8.9 %, respectively, compared to the control samples without fly ash.

3.2. Compressive strength testing of SCC

Concrete samples were prepared and cured according to TCVN 3105:2022 [17] and TCVN 3118:2022 [18] standards, respectively. The compressive strength tests were conducted on 10x10x10cm samples at 28 days and 90 days. The results showed that the use of a high volume of fly ash in the binder significantly reduced the compressive strength of SCC. The compressive strength of CPF70 and CPF80 mixes at 28 days was 25.1 MPa and 21.2 MPa, respectively, representing a reduction of approximately 56.7 % and 63.4 % compared to the CPF0 mix without fly ash. However, at 90 days, due to the pozzolanic reaction between fly ash and the hydration products of cement, the compressive strength of mixes with high fly ash volume improved significantly. CPF70 and CPF80 mixes achieved compressive strength values of 49.4 MPa and 28.3 MPa, respectively, at 90 days (Figure 1). According to TCVN 327:2024, which specifies compressive strength requirements for structures ranging from 25 MPa to 50 MPa, the use of fly ash with a very high volume of up to 80 % can meet the requirements for many structures in the coastal environment in terms of compressive strength. Figure 1 illustrates the compressive strength results of SCC mixes at 28 days and 90 days.

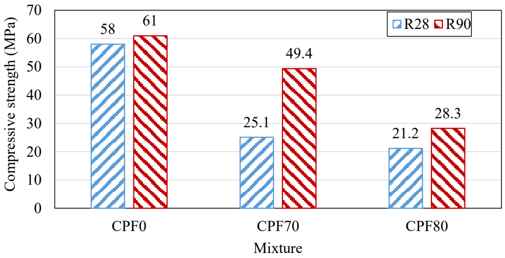


Figure 1. Compressive strength results of scc mixes at 28 days and 90 days.

3.3. Chloride ion permeability testing of SCC

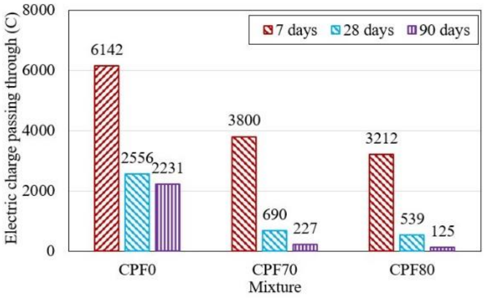


Figure 2. Chloride ion permeability test results of SCC mixes.

The chloride ion permeability was evaluated using the rapid chloride permeability test (RCPT) according to TCVN 9337:2012 [19]. The results, as shown in Figure 2, indicate that the chloride ion permeability depends on the fly ash volume in the SCC mix. At early ages (7 days), the charge passed through CPF70 and CPF80 mixes was 3800C and 3212C, respectively, representing a reduction of 38.13 % and 47.7 % compared to CPF0. At later ages (28 days), the charge passed through CPF70 and CPF80 mixes was 690C and 539C, respectively, representing a reduction of 73 % and 78 % compared to CPF0. Particularly, at 90 days, the charge passed through CPF70 and CPF80 mixes was very low, with values of 227C and 125C, representing reductions of 89.8 % and 94 % compared to CPF0. This indicates that high-volume fly ash has a significantly positive effect on reducing chloride ion permeability at later ages. According to TCVN 9337:2012, the charge passed through CPF70 and CPF80 mixes at 28 days and 90 days falls within the range of 100-1000C, indicating that the concrete belongs to the category with very low chloride ion permeability. With very low chloride ion permeability when using high-volume fly ash, SCC is suitable for many concrete structures in coastal environments.

3.4. Water absorption and dry bulk density testing of SCC

Concrete samples were cast and cured according to TCVN 3105:2022 [17]. The specimens had dimensions of 100x100x100 mm. Water absorption was determined according to TCVN 3113:2022 [20], and dry bulk density was measured according to TCVN 3115:2022 [21].

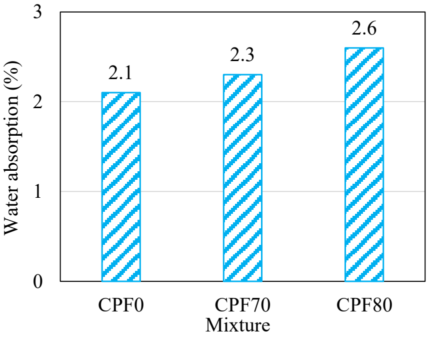


Figure 3. Water absorption test results of SCC at 28 days.

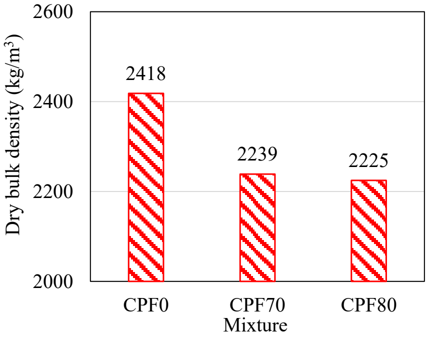


Figure 4. Dry bulk density test results of SCC at 28 days.

The water absorption results of CPF70 and CPF80 mixes at 28 days were 2.3 % and 2.6 %, respectively, representing an increase compared to the control sample CPF0, which had values of 9.5 % and 23.8 %, respectively. However, it can be observed that the water absorption of all mixes using high-volume fly ash remains very low. This is because the dense cement paste layer of SCC has low porosity and continuous voids, making water ingress into SCC very difficult. The low water absorption of SCC is an important characteristic to reduce water ingress and the corrosion of steel reinforcement in coastal structures. Figure 3 illustrates the water absorption test results of SCC mixes.

The dry bulk density of CPF70 and CPF80 mixes was 2239 kg/m3 and 2225 kg/m3, respectively, which is lower than CPF0 by 7.4 % and 7.9 %, respectively. This reduction is attributed to the lower specific gravity of fly ash compared to cement. The reduction in dry bulk density when using high-volume fly ash helps to reduce the structural load and contributes to reducing construction costs. Figure 4 shows the results of the dry bulk density test of SCC at 28 days.

3.5. Evaluation of energy consumption during concrete production

The sustainability of high-volume fly ash SCC was assessed through the energy consumption index during production. In this study, the authors compared the energy consumption during the production process between high-volume fly ash SCC mixes with 70 % and 80 % fly ash volume (CPF70, CPF80) and those without fly ash (CPF0), as well as with conventional concrete mixes of grade 200 (BT200) and grade 250 (BT250). The energy consumption standards during concrete material preparation were taken from the study by Hui Zhao [22].

Table 2. Energy Consumption Calculation for 1m^3 of Concrete.

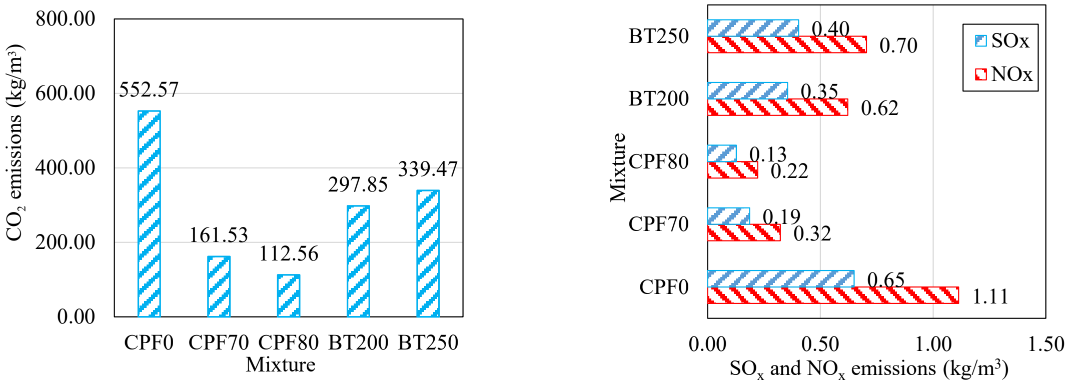
Material	Standard (MJ/kg)	CPF0	CPF70	CPF80	BT250	BT200
Cement	4.8	2911.2	791.5	520.8	1794.2	1567.4
Fly Ash	0.12	46.2	46.2	52.1	0.0	0.0
Sand	0.08	59.9	59.9	59.9	62.1	63.5
Stone	0.08	61.6	61.6	61.6	95.3	97.6
Sp	16.46	101.2	90.4	89.2	0.0	0.0
Water	0.21	44.6	40.4	39.9	40.5	40.5
Total (MJ/m^3)		3224.7	1090.0	823.4	1992.2	1769.0

The calculation results in Table 2 show that the energy consumption for producing 1m^3 of concrete for CPF0, CPF70, CPF80, BT250, and BT200 mixes is 3224.7 MJ/m^3, 1090.0 MJ/m^3, 823.4 MJ/m^3, 1992.2 MJ/m^3, and 1769.0 MJ/m^3, respectively. The use of high-volume fly ash significantly reduces energy consumption during SCC production. CPF70 and CPF80 mixes reduce energy consumption compared to CPF0 by 66.19 % and 74.46 %, respectively. CPF70 also reduces energy consumption compared to BT250 by 45.28 %, while CPF80 reduces it by 53.45 % compared to BT200. Using fly ash to replace 70 % - 80 % of cement by weight, the energy consumption during SCC production is lower than that of conventional concrete with equivalent strength by 45.28 - 53.45 %.

3.6. Assessment of emissions generated in concrete production

The effectiveness of SCC is assessed through its environmental impact during the production process. In this study, CO_2 and harmful gases such as NO_x and SO_x emissions were calculated based on Table 3 following the guidelines provided by Hui Zhao [22].

According to the calculated results in Figure 5, the amounts of CO_2, SO_x, and NO_x emissions produced during the production of concrete with different mixtures (CPF0, CPF70, CPF80, BT250, BT200) are respectively (552.57kg/m^3, 0.65kg/m^3, 1.11 kg/m^3), (161.53kg/m^3, 0.19kg/m^3, 0.32kg/m^3), (112.56kg/m^3, 0.13kg/m^3, 0.22kg/m^3), (112.56kg/m^3, 0.13kg/m^3, 0.22kg/m^3), (339.47kg/m^3, 0.4kg/m^3, 0.7kg/m^3), (297.85kg/m^3, 0.35kg/m^3, 0.62kg/m^3). The utilization of SCC with high proportions of fly ash (70%, 80% by weight of cement) significantly reduces the emissions into the environment during the production process. Specifically, compared to CPF0, the CO_2, SO_x, and NO_x emissions of CPF70 and CPF80 mixtures decrease by (70.76 %, 71.03 %, 71.39 %) and (79.63 %, 80.10 %, 80.45 %) respectively. The CO_2, SO_x, and NO_x emissions of CPF70 and CPF80 are reduced compared to BT250 and BT200 by (52.41 %, 54.26 %, 53.95 %) and (62.21 %, 64.33 %, 64.13 %) respectively.



(a) CO_2 emissions (kg/m^3) (b) SO_x and NO_x emissions (kg/m^3)

Figure 5. Emissions generated during concrete production.

Table 3. Emission factors for CO_2, NO_x, SO_x of materials [22].

Material	Unit	CO_2	NO_x	SO_x
Cement	kg	0.885	1.79×10^{-3}	1.05×10^{-3}
Fly Ash	kg	1.96×10^{-2}	1.02×10^{-6}	8.36×10^{-6}
Sand	kg	2.34×10^{-2}	1.52×10^{-5}	9.49×10^{-6}
Stone	kg	5.71×10^{-2}	200×10^{-5}	3.00×10^{-6}
Sp	kg	0.34	-	-
Water	kg	1.96×10^{-4}	-	-

3.7. Assessment of material costs in concrete production

Material costs are a crucial indicator for evaluating the sustainability of SCC. The authors conducted calculations for the material costs of SCC mixtures (CPF0, CPF70, CPF80) and traditional concrete with compressive strength equivalent to grade 200, B4 (BT200), grade 250, B6 (BT250). The calculation was carried out in the coastal area of Loc Ha district, Ha Tinh province. Material quantities for BT200 and BT250 concrete were referenced from DM 12/2021 [23] by the Ministry of Construction. Material prices were obtained from the Q4 2023 price list in Loc Ha district, Ha Tinh province.

The calculated results (Table 4 and Figure 6) show that the material costs for CPF0, CPF70, CPF80, BT200, BT250 mixtures are 1,368,614 VND/m^3, 770,927 VND/m3, 698,327 VND/m^3, 843,081 VND/m^3, 908,510 VND/m^3 respectively. Increasing the proportion of fly ash in the mix reduces the material costs of HVFA SCC. Specifically, the material costs of CPF70 and CPF80 mixtures are reduced by 43.67 % and 48.98 % respectively compared to CPF0. The material cost of CPF70 is reduced by 15.14 % compared to BT250, while CPF80 is reduced by 17.16 % compared to BT200.

Table 4. Material cost calculation for SCC and traditional concrete.

Mixture	Cement (VND/m^3)	Fly ash (VND/m^3)	Stone (VND/m^3)	Sand (VND/m^3)	Sp (VND/m^3)	VMA (VND/m^3)	Water (VND/m^3)	Total (VND/m^3)
CPF0	937.043	0	132.500	128.366	153.750	16.000	955	1.368.614
CPF70	254.771	96.175	132.500	128.366	137.250	21.000	866	770.927
CPF80	167.633	108.475	132.500	128.366	135.500	25.000	854	698.327
BT200	504.443	0	201.930	135.840	0	0	869	843.081
BT250	577.521	0	197.160	132.960	0	0	869	908.510

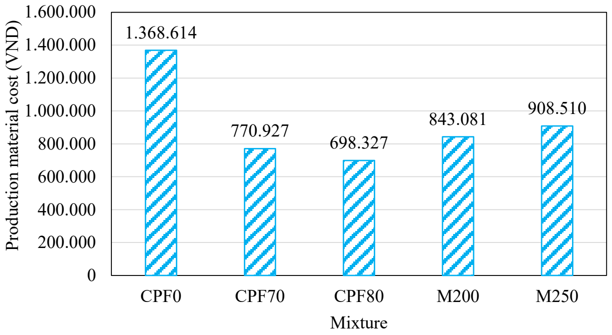


Figure 6. Material cost calculation for SCC and traditional concrete.

Table 5. Material quantities for 1m^3 of BT200, BT250 [23].

Mixture	Code	Cement (kg)	Aggregate (kg)	Sand (kg)	Water (liters)
BT200	11.11223	326.50	0.762	0.566	193
BT250	11.11224	373.08	0.744	0.554	193

(Note: The material quantities for waterproof concrete in Table 5 have been adjusted to increase cement by 5 %, sand by 12 %, and decrease aggregate accordingly.)

In concrete production, cement costs typically account for about 60-67 % of the total cost. With relatively high cement prices around

1,545,000 VND/ton in Ha Tinh province, the cost of fly ash is less than 20 % of the cement cost. Therefore, producing high-volume fly ash SCC with high-volume fly ash significantly reduces production costs. Moreover, advantages such as no need for vibration compaction and fast construction progress mean that the actual costs of high-volume fly ash SCC may be even lower than the calculated figures above. Table 5 presents the material quantities for traditional concrete mixtures.

4. Conclusions

The research results indicate that SCC using high-volume fly ash possesses suitable technical properties for coastal construction projects. Additionally, applying this type of concrete significantly reduces energy consumption, environmental emissions, and production costs.

SCC with fly ash substitution rates of 70 % and 80 % by weight achieves compressive strengths of 25.1MPa and 21.2MPa at 28 days, and 49.4 MPa and 28.3 MPa at 90 days respectively. Chloride ion permeability is very low, with chloride ion penetration depths of 690C and 539C at 28 days, and water absorption rates of approximately 2.3 % and 2.6 %. Dry bulk densities at 28 days are 2239 kg/m^3 and 2225 kg/m^3.

Compared to traditional concrete with equivalent compressive strength (BT200, BT250), SCC with fly ash substitution rates of 70 % and 80 % by weight reduces energy consumption during production by 45.1 % and 53.4 % respectively. CO_2, NO_x, SO_x emissions are reduced by (52.41 %, 54.26 %, 53.95 %) and (62.21 %, 64.33 %, 64.13 %) respectively. Material production costs (in Ha Tinh province) decrease by 15.14 % and 17.16 % respectively.

Using SCC with high-volume fly ash for coastal projects is a sustainable development solution.

References

[1]. Hoang Van Khai, "Developing Vietnam's maritime economy - Potential and challenges", 17/02/2020. [Online]. Available: https://mof.gov.vn/webcenter/portal/vclvcstc/pages_r/l/chi-tiet-tin?dDocName=MOFUCM172376. [Accessed: 30/03/2024].

[2]. Dong Kim Hanh & Duong Thi Thanh Hien. "Corrosion of reinforced concrete and anti-corrosion solutions for reinforced concrete structures in the maritime environment of Vietnam." *Journal of Hydraulic Engineering and Environment* (2011): 44-49.

[3]. TCVN 327:2004. *Concrete structure and reinforced concrete - Requirements for corrosion protection in maritime environments*. Ministry of Science and Technology, Vietnam.

[4]. Nguyen Viet Trung (2002), Self-compacting concrete technology and its application in cable-stayed bridge construction, *Conference on New Technologies in Transportation Infrastructure Construction and Management in Vietnam*, 07/2002.

[5]. STANKOVIC, Tatjana. "Investigations as Regard New Technological Features of Concrete for the Construction of Modern Roads Structures." *Journal of Civil Engineering* 15.2 (2007): 10-19.

[6]. Le Sy Trong & Hoang Pho Uyen, "Evaluation of the technical-economic efficiency of self-compacting concrete when used for mobile crossbar dams," *Journal of Science and Technology of Hydraulic Engineering*, No. 14 -2013.

[7]. Thomas, M. D. A. *Optimizing the use of fly ash in concrete*. Vol. 5420. Skokie, IL, USA: Portland Cement Association, 2007.

[8]. Malhotra, V.M. and Mehta, P.K., High-Performance, High-Volume Fly Ash Concrete. Supplementary Cementing Materials for Sustainable Development Inc., Ottawa, Canada (2005): 1-124.

[9]. Atis, C.D., "High-Volume Fly Ash Concrete with High-Strength and Low Drying Shrinkage," *Journal of Materials in Civil Engineering*, ASCE 15.2 (2003): 153-156.

[10]. Thomas M. D. A., M. H. Shehata, & S. G. Shashiprakash. "The use of fly ash in concrete: classification by composition." *Cement, concrete, and aggregates* 21.2 (1999): 105-110.

[11]. Thomas, M.D.A., "Prevention of Reinforcement Corrosion in Concrete Structures. Part I: Carbonation-Induced Corrosion". *Canadian Civil Engineer: Special Issue on Durability of Concrete Structures*, May, 2004, 22-25.

[12]. Naik, Tarun R., et al. "Long-term performance of high-volume fly ash." *ACI Mater. J* 100 (2003): 150-155.

[13]. Shehata, Medhat H., and Michael DA Thomas. "The effect of fly ash composition on the expansion of concrete due to alkali–silica reaction." *Cement and Concrete Research* 30.7 (2000): 1063-1072.

[14]. Tikalsky, P. J. "Influence of fly ash on the sulfate resistance of concrete." *Materials Journal* 89.1 (1993): 69-75.

[15]. Okamura, Hajime, and Kazumasa Ozawa. "Mix design for self-compacting concrete." *Concrete library of JSCE* 25.6 (1995): 107-120.

[16]. TCVN 12209:2018. *Self-compacting concrete - Technical requirements and test methods*, Ministry of Science and Technology, Vietnam.

[17]. TCVN 3105:2022. *Concrete mixtures and concrete - Sampling*, production and maintenance of test samples, Ministry of Science and Technology, Vietnam.

[18]. TCVN 3118:2022. *Concrete - Method for determining compressive strength*, Ministry of Science and Technology, Vietnam.

[19]. TCVN 9337:2012. *Heavyweight concrete - Determination of chloride ion permeability by charge measurement method*, Ministry of Science and Technology, Vietnam.

[20]. TCVN 3113:2022. *Concrete - Method for determining water absorption*, Ministry of Science and Technology, Vietnam.

[21]. TCVN 3115:2022. *Concrete - Method for determining bulk density*, Ministry of Science and Technology, Vietnam.

[22]. Zhao, Hui, et al. "Sustainable self-compacting concrete containing high-amount industrial by-product fly ash as supplementary cementitious materials." *Environmental Science and Pollution Research* 29.3 (2022): 3616-3628.

[23]. Circular No. 12/2021/TT-BXD dated August 31, 2021 "Issuing construction norms," *Ministry of Construction*. Effective from October 15, 2021.