Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

Research article

UDC 666.97

DOI: 10.34910/MCE.117.2

High-performance concrete produced with locally available materials

B.I. Bulgakov ✉, ***V.Q.D. Nguyen***, ***A.V. Aleksandrova***, ***O.A. Larsen***, ***N.A. Galtseva***

Moscow State University of Civil Engineering (National Research University), Moscow, Russia

✉ *fakultetst@mail.ru*

Keywords: superplasticizer, silica fume, sulfate-resisting Portland cement, silica flour, fly ash, high-performance concrete, strength and durability

Abstract. Vietnam is one of the countries most severely affected by climate change and sea level rise, especially in the south. High-performance concrete appears to be a better choice for strong and durable structures. The primary objective of this research was to use locally available materials to produce HPC reaching compression strength of over 100 MPa and suitable for Vietnamese climatic conditions and environment. The materials locally available in Vietnam used in the study included: sulfate-resisting Portland cement (PCSR40), crushed granite as coarse aggregate (size 9.5÷19 mm), river sand with fineness modulus of 3.0, Sika®Viscocrete®-151 type superplasticizer, mineral materials (class F fly ash and silica fume), and potable water. All concrete mixtures were designed according to TCVN 10306-2014 standard. For compressive strength, concrete samples were tested after 3, 7, 28, 56, and 450 days, while the tests for splitting tensile and flexural strengths, water absorption and permeability were conducted after 28 days. In this experimental research, the greatest compressive strength values obtained at 450 days of age were 95.426 MPa in a mix containing 10 %SF + 20 %FA + 20 %Qp and 101.597 MPa in a mix containing 12.5 %SF + 20 %FA + 20 %Qp. The results showed that the optimum high-performance concrete mixes used for construction in aggressive corrosive environment of Southern Vietnam contain 7.5 %SF + 30 %FA, 10 %SF + 20 %FA, 10 %SF + 30 %FA, 12.5 %SF + 20 %FA, respectively. This study showed that the HPC produced with locally available materials in Vietnam can have compressive strength exceeding 110 MPa as well as other excellent mechanical properties. All of this can be achieved simply by using materials available at the local markets, provided they are carefully selected and properly mixed to optimize grain size distribution.

Citation: Bulgakov, B.I., Nguyen, V.Q.D., Aleksandrova, A.V., Larsen, O.A., Galtseva, N.A. High-performance concrete produced with locally available materials. Magazine of Civil Engineering. 2023. Magazine of Civil Engineering. 117(1). Article no. 11702. DOI: 10.34910/MCE.117.2

1. *Introduction*

In the late 1980s, a number countries launched major specific research programs on high-performance concrete (HPC), among which are the USA [1], Norway [2], Canada [3], France [4], Switzerland [5], Australia [6], Germany [7], Japan [8], Korea [9], China [10], Taiwan [11] etc. European and UK standards for HPC define HPC as "High workability concrete; Self-consolidating concrete (SCC); Foamed concrete; High strength concrete; Lightweight concrete; No-fines concrete; Pumped concrete; Sprayed concrete; Waterproof concrete; Autoclaved aerated concrete; Roller-compacted concrete" following ACI [12]. Russian documents do not provide such a classification. However, Professor Yu.M. Bazhenov considers the concrete to be high-quality if it meets the requirements high strength, durability, workability, and stability of the volume [13–15]. In recent years, HPC was used in the manufacture of elements of the tunnel under Bolshaya Dmitrovka street, tubes of the Lefortovsky tunnel in Moscow, and in the construction of multi-story centers "Moscow City", cooling towers working under the threat of acid, and even in the construction of load-bearing walls of a house [16–17] as well as a number of other transport and industrial construction projects. In Vietnam, HPC is a relatively new research topic, not much research has been published yet. Vietnam has begun to apply high-strength concrete with aggregate and conventional cement using superplasticizer, with water to cement ratio of about 0.35–0.40, with slump reaching 15–20 cm, kept at least 60 minutes, with compression strength of 50–70 MPa and early strength $R_7 = 0.85R_{28}$. This is the type of concrete used mainly in houses, bridges, roads, and irrigation structures in Vietnam. However, Vietnam is located in the wet-hot dry tropics with high chloride ion content. Long seacoast of more than 3200 km is immediately affected by climate change, rising sea water, sea water intrusion + chemical wastewater from industrial areas, which is one of the basic causes of the deterioration of the construction. The impact of the "sour" and "salty" environments leads to corrosion and destruction of the construction due to the quality of concrete that does not meet the requirements of corrosion resistance in aggressive corrosive environment as well. In order to solve this problem, HPC was designed with properties far superior to conventional concrete both on strength and durability, which helps extend the service life of concrete structures. For this reason, it is a perfect choice for constructions in harsh climatic and environmental conditions [18–20].

Ahmet Benli [21] studied the mechanical and durability properties of self-compacting mortars (SCM) by addition of fly ash (FA) and silica fume (SF) in concrete mixtures partially replacing cement at varying levels from 5 to 25 % by weight of FA and 5 %, 10 %, and 14 % by weight of SF. Results show that binary mixes of FA reduce strength when the content of FA increases. The binary mix with 10 % by weight of silica fume reaches the highest tensile strength of 10.5 MPa and compressive strengths of 81.5 MPa after 180-day curing. In that time, the mixture containing 5 % FA reached compressive strength of 84.3 and flexural strength of 10.21 MPa. On the other hand, the ternary mixes with 10 % by weight of FA and SF got 84.4 MPa for compressive strength and 10.09 MPa for tensile strengths.

Karthikeyan [22] researched strength and durability characteristics of HPC by changing metakaolin (MK) and silica fume content for the purpose of improving concrete mix and the life span of structures. The main parameter investigated in this study is designed concrete mix of the following composition: 0.63 t/m^3 cement + 1.15 t/m^3 coarse aggregate + 0.51 T/m^3 manufactured sand. The water/binder ratio adopted was 0.28 and superplasticizer “ViscoCrete 20 HE” dosage was fixed at 1 % of the binder mass, by which SF and MK were used individually to partially replace cement in the range of 0–15 %. The authors concluded that the optimum content of MK or SF used to partially replace cement stood at 15 %: at this level, the highest compressive strength attained was 85 MPa and 80.34 MPa for HPC(MK) and HPC(SF) specimens, respectively, which was higher compared to the other replacements.

Bilek et al. [23] conducted studies aimed at producing high-performance concrete with compressive strengths ranging from 120 to 170 MPa by using a ternary binder. Water/binder ratio was kept at a constant level of 0.225 for all mixes. The authors found an optimum composition of concrete mixture containing: 650 g Portland cement CEM I 42.5 R + 75 g metakaolin + 40 g fly ash + 35 g ground limestone + 20 g superplasticizer + 165 g water + 960 g sand + 40 g steel fibers with length of 13 mm & diameter of 0.20 mm. They achieved compressive strength of 140 MPa at the age of 28 days.

Ali Alsalman et al. [24], by using locally available materials like Portland cement (type I), steel fibers (0.02×12.7 mm), class F fly ash, chemical admixtures of polycarboxylate-based types, silica fume and river sand presented 3 different grain sizes as fine aggregate to study strength development of UHPC mixes. Their results proved that the mix containing total cementitious materials dosage at 1009 kg/m^3 had compressive strength at 155.2 MPa after 90-day curing without heat curing. When increasing the fly ash content to 20 %, compressive strength of the concrete achieved 152.1 MPa at the age of 90 days.

Ahmet Benli et al. [25] studied the influence of replacing cement with different dosages of FA type F and SF on rheological and mechanical properties, the freeze-thaw resistance in self-compacting mortars (SCM). The weight binder was kept at 640 kg/cm^3 for all mortar mixtures including replacement levels of fly ash at 25–40 % and of silica fume at 5–20 % by weight of cement, respectively, and water/binder ratio was between 0.43 and 0.50. The results proved that with SF or FA content increasing elastic modulus reduced, while the decrease in the elastic modulus of SCM containing SF was more dramatic than in SCM incorporating FA because of the deleterious effects of SF on freeze-thaw cycles. In addition, the SCM incorporating SF had compressive and flexural tensile strength higher than the control mixture and the SCM with FA at the curing age of 28 and 91 days.

Harpreet Singh et al. [26] studied concrete mix design using industrial by-products, for example, SF, FA to partially replace cement and fine aggregate at levels of 10, 15 and 20 %. Their research results showed that the optimal content of both admixtures in concrete mix was at 15 % and compressive/flexure/split tensile strength values were higher than those for ordinary concrete at the age of 28 days.

Hajek and Fiala [27, 28] studied the influence of HPC. Through the process of analysis and assessment, the authors observed that HPC is a construction material that has technology character necessary to concrete structures that need sustainability and high resilience under the impact of harsh environments, thereby extending the life of construction works and consequent social and economic improvements.

Mohamed and Najm [29] studied properties of self-consolidating concrete (SCC) by using industrial by-products, namely, ground granulated blast furnace slag (GGBS), SF, and FA to replace cement content up to 80 %, by weight of cement. The water-binder ratio adopted was 0.36 and cementitious materials content was approximately 480 kg/m^3. Glenium Sky 504 superplasticizer was used and kept constant at 1.5 % of the total weight of cementitious materials, crushed granite was used as coarse aggregate of 14 mm size with a total amount of 800 kg/m^3, fine aggregates consisted of 313.6 kg/m^3 dune sand and 582.4 kg/m^3 black sand for all 19 mixes; fly ash content was from 10 to 40 %, silica fume from 5 to 20 % or GGBS (10–80 %).The results showed that the SCC mix containing 20% fly ash had compression strength values of 67.9 MPa at 28 days, compared to 61.3, 56.5, and 55.8 MPa for 10 %, 30 %, and 40 % replacements, respectively. The mixture containing SF at 15 %, and FA at 20 %, had compressive strength higher by 44 % than control concrete at the age of 28 days. Furthermore, replacing cement with up to 40 % fly ash produced a competitive compressive strength high enough for many practical structural design applications. And 35 % is the optimum GGBS replacement ratio producing a high 28-day compressive strength of 81 MPa.

Chena et al. [30] attempted to produce HPC by using fly ash microspheres (FAM) and condensed silica fume (CSF). In their study, HPC was manufactured from the binary mixes of FAM and CSF by replacing ordinary Portland cement (OPC) with 20 %, and 40 % by weight of FAM and 10 %, 20 % by weight of CSF. The water to cementitious materials (w/cm) ratio ranged from 0.14 to 0.3. The results proved that the mix containing CSF = 20 %, when the w/cm ratio was 0.16, had the highest compressive strength of 159 MPa at the age of 28 days with flow spread = 80 mm. When the w/cm ratio was 0.3, then the compression strength was 105 MPa at the age of 28 days, with flow spread = 180 mm. The mix with FAM = 20 %, CSF = 10 %, when the w/cm ratio was 0.16, the compressive strength reached 135 MPa at the age of 28 days, flow spread = 113 mm. When the w/cm ratio was 0.3, then the compression strength reached 95 MPa at the age of 28 days, flow spread = 300 mm. From the results study we can conclude that the addition of CSF and FAM can significantly increase the packing density, consequently enhancing flowability and strength performance.

S.W. Yoo et al. [31] appraised autogenous shrinkage (AGS) in HPC with water-binder ratio of 0.3 with mineral admixtures of the following content: fly ash (0–30 %), silica fume (0–15 %), chemical admixture shrinkage reducing agent (0.5–1.0 %), and expansion agent (5–10 %). The autogenous shrinkage in HPC with FA was decreasing continuously with larger FA replacement. The AGS in HPC with SF was higher compared to that in ordinary Portland cement concrete. Use of both admixtures in adequate amount can lower autogenous shrinkage as well as improve the strength.

Elahi et al. [32] evaluated the mechanical and durability properties of HPC containing supplementary cementitious materials (SCM) such as SF, FA, and GGBFS, water to binder ratio constant was fixed at 0.3 in binary and ternary systems. In the experimental study, cement content was replaced with 70 % GGBFS, SF reached 15 %, and FA was up to 40 %. The ternary mixes containing FA or GGBFS with 50% replacement level and 7.5 % SF performed the best amongst all the mixes to resist the chloride diffusion. The replacement of 7.5 % SF performed better than other SCM for strength development. There was a benefit in the case of absorptivity with the addition of 50 % GGBS and 20 % FA compared to the control mix.

P.H Hanh et al. [33] used an experimental plan method to find the optimum proportion of the concrete mix based on preliminary proportioning according to ACI. The experiment results indicated that it is possible to make M100 grade HPC that suits marine environment by using available materials in Vietnam. It showed high impermeability (stable current of circuit 2.7–3.5 mA, destroyed time 41 days), high elastic modulus (6.5 MPa), high ability to steel adhesion (steel adhesion factor = 33.37), high strength development (60 MPa) at 3 days. Five categories of HPC namely Normal Strength Concrete (35 MPa), Medium Strength Concrete (56 MPa), High Strength Concrete (62 MPa), Very High Strength Concrete (98 MPa), Ultra High Strength Concrete (120 MPa) with slump value ranged from (100–200 mm) were designed by El Shikh [34].

Arunachalam et al. [35] performed experiments to make a comparative study on the properties of HPC with water to binder ratio of 0.28, fly ash (25 % and 50 % replacement) and without fly ash (control concrete) in the normal and aggressive environment (Al_2SO_4 and NaCl). After time curing 28-day, concrete samples continue cured in an aggressive environment until the 60th day, compressive strength has been gone down about 25 % compared to strength at age 28-day. Meanwhile, test results indicate that HPC mixtures containing FA content at levels 25 %, and 50 % by weight of the cement, have a significant increase in compressive strength for both curing environments from 7 to 60 days. HPC utilizing fly ash and micro silica as cement replacing materials were investigated [36] to study permeation related properties like permeability, porosity, and absorptivity with different curing conditions namely moist and air curing, at temperature 5 °C. Results proved above values reduced to mix containing low w/cm ratio, plus 10 % SF and FA replacement between range 15–20 %. Same permeability values were not achieved for specimens cured at 5 °C in comparison with moist and air curing.

Mohd Zain et al. [37] studied mechanical properties of HPC with four different type concrete mixtures with GGBS, SF and FA at 25 % water to binder ratios. Mineral admixtures partially replaced cement at levels of 10–50 %. The authors concluded that the mix consist of 10 % SF achieved compressive strength values of 130 MPa and 5.28×10^4 MPa of modulus of elasticity, at age 91-day when specimens cured in water at a temperature of 20 °C or wrapped by wet burlaps at temperature of 35 °C. These values were higher than compared to other mixes in the same curing conditions. This showed that the SF can influence concrete's performance, it as a filler leads to porosity reducer in concrete's microstructures.

Tamimi, A.K. [38] studied the influence of HPC mix in HCl and H_2SO_4 environments. Control mix contained 400 kg of ordinary Portland cement, aggregates with max size 15 mm, melamine superplasticizer and had the water/binder ratio at 0.35 and 0.4. The author used 10 % silica fume and various percentages (40, 60, and 80 %) of pulverized FA to partially replace cement content. The results indicate that the mix containing 10 % SF combined with 60 % pulverized fly ash and 30 % OPC would produce optimum protection against acid attacks, which was proven through experiments in the acidic environment (with 1 % HCl and H_2SO_4 content), at 20 °C temperature.

Vietnam is one of the countries most severely affected by climate change and sea level rise, especially in the southern part [39–43]. To solve this problem, high-performance concrete appears to be a better choice for a strong and durable structure. Therefore, the primary objective of this research is to produce HPC with compression strength of over 100 MPa suiting Vietnam climatic conditions and environment by means of using locally available materials.

2. Methods and Materials

In this study, the physico-mechanical properties of concrete are determined through the change in compressive strength and loss of weight of the concrete samples immersed in three environments after a period of 450 days. (1) The saline-alkaline medium was chosen to soak experimental samples in Hung Thanh of Dong Thap province: it characterizes the environment in the Mekong River Delta region (Southern Vietnam); (2) Seawater environment used to cure the concrete samples is from Chan May Port in Thua Thien – Hue Province (South Central Coast – Central Vietnam); (3) and potable water used to cure control concrete is the control environment. The chemical composition of the sample immersion environments is shown in Table 1 and 2.

Table 1. The composition of the main ions in source of water used for concrete sample curing.

Source of water	pH	SO_4^{2-} (mg/l)	Cl^- (mg/l)	Mg^{2+} (mg/l)	Ca^{2+} (mg/l)
Potable water	6.53	103	182		
Saline-alkaline environment	4.43	490	97.2	696	560
Seawater	7.8 – 8.4	$(1.4 \div 2.5) \times 10^3$	$(6.5 \div 18.0) \times 10^3$	$(0.2 \div 1.2) \times 10^3$	

Table 2. The pH value and the salt content (g/l) of saline-alkaline medium experimental samples were soaked in.

Months	1	2	3	4	5	6	7	8	9	10	11	12	Aver. value
pH	5.08	5.02	4.56	4.10	3.52	3.12	3.13	3.46	3.96	5.22	6.2	6.05	4.43
Salt content	25.9	25.5	24.3	23.3	22.3	22.0	22.2	23.7	25.2	25.6	26.1	27.0	24.43

The material types like cement, aggregates, mineral materials etc., used in the mix before, underwent preliminarily physical and chemical analyses to determine whether they are in compliance with the standard used. A total of 15 different mixes with concrete grades higher or equal to M80 were designed, in compliance with Vietnamese Standard TCVN 10306-2014 “High strength concrete-proportional design with cylinder sample”, and their properties, such as workability, as well as strength and durability, were tested. The total dosage of cementitious materials was fixed at 550 kg/m^3. Similarly, the dose of aggregates, chemical admixture, and w/cm ratio were fixed in all the mixes. Substituted mineral materials like silica fume with content selected as (0 %, 5 %, 7.5 %, 10 %, 12.5 %) were combined with class F fly ash at content levels (0 %, 20 %, 30 %, 40 %) to partially replace sulfate-resistant cement by weight in the mixes. Compressive strength was tested using 15 cm^3 cube samples; tensile strength as well as modulus of elasticity, were tested using cylindrical samples (d×h=15×30 cm); 15×15 cm cylinders and 10×10×40 cm prisms were utilized to test permeability/water absorption and flexural strength, respectively.

Here is the list of other materials used to design the HPC mixtures:

1. Cement $PC_{SR}40$ (type 5) of Luks Cement (Vietnam) Limited is sulfate-resistant Portland cement with the following parameters: compressive strength at 3 days 25.7 MPa and 28 days 46.5 MPa; time of initial setting 130 min, and final setting 175 min; C_3A content 2.49 % and C_4AF+2C_3A content 21.23 %; specific gravity 3.15 g/cm^3; sulfate resistance at 14 days expansion 0.0156 %. Other components are presented in Table 3. The type of the cement used complied Vietnamese Standard TCVN 7711-2013 "Sulfate resistant blended Portland cements".

2. Crushed aggregate with maximum size of 19 mm (60 %) and 9.5 mm (40 %) from a local source (Ga Loi stone-pit in Central region of Vietnam) was used as coarse aggregate with the following parameters: specific gravity 2.68 g/cm^3, volume of coarse aggregates 2.63 g/cm^3, water absorption 0.5 %, fineness modulus about 6.5÷6.8, and average strength 105.593 MPa.

3. Natural sand exploited from Huong river, Vietnam, with fineness modulus of 3.0, specific gravity of (2.6–2.65) g/cm^3, moisture of 1 %, was used as fine aggregate in compliance with Vietnamese Standard TCVN 7570-2006 "Aggregates for concrete and mortar – Specifications".

4. Water used to mix and cure the concrete complied Vietnamese Standard TCVN 4506-2012 "Water for concrete and mortar - Technical specification".

5. The chemical plasticizing admixture used was Poly-Carboxylic Ether Sika®ViscoCrete®-151, which is brown in color with specific gravity of 1.075–1.095 kg/l. Its recommended dosage for 1 kg of cement is 0.018 l, which is used for effective workability in accordance with Vietnamese Standard TCVN 8826-2011/2 "Chemical admixtures for concrete" (ASTM C494 Type G).

6. Fly ash, available as a byproduct of the thermal power plants Pha Lai (Vietnam), was used in dry powder form. Class F fly ash was supplied and rounded to angular shape. It had low CaO content and exhibited Pozzolonic properties in accordance with Vietnamese Standard TCVN 10302-2014 "Activity admixture - Fly ash for concrete, mortar and cement".

7. Silica Fume is being used increasingly as a supplementary cementing material for concrete. Admixture in dry densified form obtained from Sikacrete® PP1 – Sika limited Vietnam has particle size < 0.1 µm and specific gravity approximately 2.15 g/cm^3 in accordance with Vietnamese Standard TCVN 8827-2011 "Highly activity puzzolanic admixtures for concrete and mortar - Silicafume and rice husk ash".

8. Quartz sand powder used in this study has specific gravity 2.56 g/cm^3, has a form of white powder with particles size ranging from 5 to 10 µm partially replacing fine aggregate. Quartz powder is milled from local silica white sand in the Central region of Vietnam.

Table 3 gives the physicochemical composition of material types used in the mix.

Table 3. The physicochemical composition of material types used in the mix.

Compositions	Cement $PC_{SR}40$	Fly ash	Silica Fume	Quartz powder
Chemical constituent (%)				
CaO	62.10	0.70	0.31	0.051
SiO_2	20.59	57.42	92.49	99.72
Al_2O_3	3.82	24.07	0.868	0.0429
Fe_2O_3	5.10	6.10	1.90	0.039
SO_3	2.05	0.30	0.3	–
BaO	1.89	–	–	–
MgO	1.701	0.951	0.841	0.0369
MnO	1.249	2.622	0.141	–
K_2O	0.630	3.612	1.231	0.0059
Na_2O	0.135	0.27	0.38	0.020
TiO_2	0.12	0.70	–	0.044
Loss of ignition	1.07	5.74	1.68	0.042
Physical properties				
Specific gravity	3.15	2.34	2.15	–
Blaine's fineness, cm^2/g	3350	3728	16028	–
Fineness (90-µm sieve)	0.7	–	–	–
Bulk density (kg/l)	–	2.19-2.56	0.50-0.70	–

The HPC was produced by mixing the designed mix proportions of cement, FA, SF, Qp, SP, and water together following the existing mix design methods with a standard mixer complying with Vietnamese Standard TCVN 10306:2014 "High strength concrete-proportional design with cylinder sample" and conforming to ACI 211.1-91 “Standard Practice for Selecting Proportions for Normal Heavyweight, and Mass Concrete”, Russian Code Design SP 28.13330.2017 “Protection against corrosion of construction”, Interstate Standard GOST 26633-2015. To start with the experiments, a control mix with target strength of 80 MPa and slump of 50÷100 mm was obtained without addition of any mineral admixtures and also with no Qp content. Mix proportions for 1 m^3 HPC mix consisted of total dosage binder 550 kg/m^3 + 1088 kg/m^3 coarse aggregate + 621.7 kg/m^3 fine aggregate + 156 l/m^3 water + 9.9 l/m^3 superplasticizer (similar to 1.8 % by mass of binder), entrapped air is 2 %, and w/b ratio is fixed at 0.3, while sand was partially replaced by 20 % quartz sand flour: these parameters remained fixed for different 15 mixes. The total dose of mineral substitutes for cement is represented by the $(SF)_{\alpha}(FA)_{\beta}$ formula, where α and β are the percentages of SF and FA, respectively, to replace cement in the mixture. The authors proposed mix combinations categorized into four SF replacement levels (5 %, 7.5 %, 10.5 %, and 12.5 %) and three FA replacement levels (20 %, 30 %, and 40 %). In each of the SF series, the FA content was set at 20 %, 30 % and 40 %, as shown in Table 4.

First, the dry materials (cement, SF, FA, fine and coarse aggregates, quartz sand powder) were blended for 2–3 min inside a plastic bag in dry form. Secondly, water containing the plasticizer was added and blended for another 4–5 min. After 6–8 min in the mixer or until concrete mix achieved the homogeneous and uniform consistency, during mixing, temperature varied following ambient temperature from 28–39 °C. The slump of the fresh concrete mixes was determined by Abrams cone (d×D×H = 100×200×300 mm) according to Vietnamese Standard TCVN 3016-1993 “Heavyweight concrete compounds – Slump test” and Interstate Standard GOST 10181-2014 “Concrete mixtures. Methods of testing”. After that, the concrete mixes were put into different casting molds of cubes/cylinders/prisms specimens and preserved at room temperatures around 30±2 °C until 24 hours. Then the specimens were stripped from molds and transferred to a fresh-water tank for curing until the time of testing. The specimens strength was tested after 3d, 7d, 28d, and 56-day curing. Vietnamese Standard TCVN 10303-2014 “Concrete - Control and assessment of compressive strength” was used to test compressive strength, while Vietnamese Standard TCVN 3119-1993 “Concrete-Method for determination of flex. Tensile strength” was used for flexural/tensile strength tests according to Interstate Standard GOST 18105-2018 “Concretes. Rules for control and assessment of strength”. Concrete strength testing machines (Matest model C089-17N (3000 kN) and TYPE-2000) were used for strength tests. The loading rates applied in the compressive and tensile splitting strength tests were 10 kN/s and 1.6 kN/s, respectively. All experiments on mechanical properties and durability characteristics of concrete were performed in laboratory LAS-XD 578, which is a synthetic laboratory for testing building materials and construction quality in central Vietnam directly under Vietnam Institute for building science and technology (IBST Vietnam). Table 5 shows the number of specimens cast and the testing arrangement.

3. Results and Discussion

There are numerous benefits in incorporating SCM into HPC mix design, including an improvement in workability of fresh concrete, reducing/eliminating free lime content, decreasing the C/S ratio of C-S-H in hardened cement pastes, mitigating alkali-aggregate reactions, etc. The products resulting from the reactions between lime and SCM refine the pore structure and reduce the permeability of hardened pastes.

Table 5 represents the required range of slump values within 105–270 mm. In theory, the addition of mineral admixtures (MA) finer than cement to fill into the voids between the cement grains and the addition of another even finer MA to fill into the voids between the larger particles should be able to reduce the voids to a greater extent than it is possible with the addition of just one MA. It is caused by the fact that the added fillers which are more finely-powdered than cement particles may be inert. It means that on the one hand they do not have chemical reactivity and in this case act as an additive that seals the structure of concrete hardened cement paste, on the other hand they may be active and participate in pozzolanic reactions, producing more C-S-H gel to form the structure of hardened concrete [43]. As usual FA particles which are spherical in shape and more finely-powdered than the particles of used Portland cement can fill the voids between its grains, while more dispersed SF particles < 0.1 μm in size can fill the voids between the particles of FA and cement. Such subsequent filling of voids will boost the hardened cement paste density by optimizing of density packaging of finely-powdered particles in its structure. In addition, finely-powdered mineral additives, in particular fly ash, may have a plasticizing effect, increasing the workability of the concrete mixture [44]. Due to the spherical shape of the fly ash particles, they have the effect of ball bearings. As a result, good conditions for increasing the mobility of neighboring particles in the concrete mixture are formed. Portland cement in the binder composition can be partially replaced by fly ash, which is cost-effective [45-47]. The quartz sand powder particles will fill the voids between the grains of aggregates. It will create the most optimal density packaging for the microstructure of the Portland cement - SF - FA - quartz powder filler matrix.

Table 4. Mix proportions of 1 m³ concrete.

Mix No.	Supplementary cementitious materials, kg/m³					Aggregates, kg/m³						Water	Super plasticizer		(W+SP)/B	Slump	Material cost
	Cement PC$_{CR}$40	Silica fume		Fly ash		Coarse aggregate		Fine aggregate	Quartz sand powder								
	kg	%	kg	%	kg	kg	C/F	kg	%	5µm	10µm	liter	%	liter	W/B	mm	USD
M1	550	-	-	-	-	11088	1.75	621.7	-	-	-	156	1.8	9.9	0.3	105	75.26
M2	550	-	-	-	-	1088	1.75	497.4	20	62.2	62.2	156	1.8	9.9	0.3	185	77.21
M3	412.5	5.0	27.5	20	110	1088	1.75	621.7	0	0	0	156	1.8	9.9	0.3	245	82.91
M4	412.5	5.0	27.5	20	110	1088	1.75	497.4	20	62.2	62.2	152	1.8	9.9	0.3	220	83.96
M5	357.5	5.0	27.5	30	165	1088	1.75	497.4	20	62.2	62.2	156	1.8	9.9	0.3	260	81.21
M6	302.5	5.0	27.5	40	220	1088	1.75	497.4	20	62.2	62.2	156	1.8	9.9	0.3	265	78.46
M7	398.8	7.5	41.3	20	110	1088	1.75	497.4	20	62.2	62.2	156	1.8	9.9	0.3	260	90.08
M8	343.8	7.5	41.3	30	165	1088	1.75	497.4	20	62.2	62.2	156	1.8	9.9	0.3	260	87.33
M9	288.8	7.5	41.3	40	220	1088	1.75	497.4	20	62.2	62.2	156	1.8	9.9	0.3	265	84.58
M10	385	10	55	20	110	1088	1.75	497.4	20	62.2	62.2	156	1.8	9.9	0.3	245	96.20
M11	330	10	55	30	165	1088	1.75	497.4	20	62.2	62.2	156	1.8	9.9	0.3	265	93.45
M12	275	10	55	40	220	1088	1.75	497.4	20	62.2	62.2	156	1.8	9.9	0.3	270	90.71
M13	371.3	12.5	68.8	20	110	1088	1.75	497.4	10	62.2	62.2	156	1.8	9.9	0.3	240	102.32
M14	316.3	12.5	68.8	30	165	1088	1.75	497.4	10	62.2	62.2	156	1.8	9.9	0.3	230	99.57
M15	261.3	12.5	68.8	40	220	1088	1.75	497.4	10	62.2	62.2	156	1.8	9.9	0.3	265	96.823

Table 5. Test results of mechanical properties for varying mineral admixtures replacement levels in high-performance concrete.

Mix No.	**Compressive strength of concrete cured** in freshwater environment, MPa				**Compressive strength and weight of concrete cured** in corrosive medium, MPa							Splitting tensile strength, MPa	Flexural strength, MPa
					Seawater environment		Saline-alkaline medium						
	3 days	7 days	28 days	450 days	450 days	Str. loss (%)	450 days	Str. loss (%)	M_1^{28}(g)	M_2^{450}(g)	Mass loss (%)	28 days	28 days
M1	67.6	71.1	83.6	86.4	86.4	0.4	82.6	8.1	8320	8145	2.1	5.70	7.85
M2	72.6	82.6	89.3	95.1	94.3	0.8	93.8	1.3	8310	8299	0.1	5.99	9.16
M3	41.3	62.2	65.3	67.3	65.7	2.4	61.0	9.4	8330	8159	2.1	4.86	7.84
M4	52.4	76.0	81.8	92.8	92.1	0.8	91.3	1.6	8100	8085	0.2	5.70	8.77
M5	67.3	73.0	80.2	86.5	85.8	0.8	84.4	2.4	8238	8225	0.2	5.60	8.32
M6	56.7	61.0	70.8	78.1	75.9	2.8	74.4	4.7	8120	8096	0.3	5.13	8.16
M7	60.0	81.0	89.5	94.2	93.0	1.2	92.4	1.9	8125	8115	0.1	6.0	9.17
M8	69.3	75.0	84.0	88.4	88.1	0.4	88.0	0.5	8105	8096	0.1	5.66	8.85
M9	59.1	66.7	74.8	84.2	83.3	1.0	82.5	1.9	8050	8028	0.3	5.32	8.39
M10	62.2	81.9	87.9	95.4	94.9	0.5	94.0	1.5	8150	8125	0.3	5.93	9.10
M11	63.9	67.5	88.8	92.6	91.6	1.1	91.4	1.3	8105	8078	0.3	6.06	9.34
M12	65.3	72.4	85.9	91.6	82.9	2.6	79.7	6.4	8090	8046	0.5	6.08	9.26
M13	59.0	83.8	91.2	101.6	101.1	0.5	101.0	0.6	8143	8112	0.4	6.18	9.37
M14	72.2	76.1	84.2	92.6	87.5	0.9	86.1	2.4	8075	8059	0.2	5.76	8.90
M15	56.4	57.3	76.1	88.0	84.9	0.1	83.1	2.3	8030	7990	0.5	5.39	8.46

Note: M_1^{28}(g) is weight of sample concrete at 28 days of age, 24 h after removing from the mold and cured in freshwater tank at temperatures varying in the ambient range of 28–39 °C; and M_2^{450}(g) is weight of sample concrete at 450 days of age after the sample was removed from the freshwater tank and soaked in saline-alkaline medium at temperatures varying in the ambient range of 28–39 °C.

Then, we compared the properties of the prepared HPC samples with various cement content replaced by FA and SF as in Table 5. It can be noticed that, regarding mechanical strength, the samples completely satisfied quality requirements, except for M1 mixes only. Mutual differences in mechanical strength and permeability coefficient of HPC mixtures probably originate from the physical and chemical properties of the applied fillers, since the other components were the same in all samples.

Table 5 gives information on the properties of concrete mixtures containing 20 % quartz powder and binder content of 550 kg/m^3 including triple blending cement with two supplementary cementitious materials of SF and FA in different proportions. Table 5 shows mechanical properties gradually increasing according to curing time: the lowest value was achieved in the test at 3-day age, followed by slow augmentation from 7th to 28th day, a sharp increase starting from the 28th day in all samples, and then resulting in a gradual increase at later ages. The impact of quartz sand powder dosage on the mechanical properties of different HPC mixtures is illustrated in Fig. 1 and Fig. 3.

The average values of compressive strength for HPC mixtures obtained from 3 test samples of the same curing age are provided in Table 5. A comparison of the specimens from M2 to M13 and control mix specimen M0 under different curing periods and conditions is presented in Fig. 1. The compressive strength results at the age of 28 days range between 70.8–91.2 MPa and the 450-days strength of all mixes was in the range of 78.1–101.6 MPa.

At the age of 3 days, the specimen M2 had the lowest value of 52.44 MPa, while sample M5 reached the highest strength at 101.6 MPa after 450 days of curing, increasing it by 48.4 % since day 3. This indicates that the strength improved gradually with the time of curing, which is due to C-H-S gel being continuously supplemented through pozzolanic reactions. At the age of 28 days, the HPC mixtures M3, M4, M7, M9, and M5 obtained the highest values of compressive strengths among the remaining samples. The bar chart in Fig. 1 illustrates that the compressive strength of almost all samples beside control mix M0 (containing no additional materials) was low at the age of 3 days. It is interesting to see that the compressive strength of HPC with higher replacement of cement (about 40–42.5 %), such as in specimens M7 and M12, was higher than that of the control mix M0. The results displayed in Fig. 1 indicate that almost all specimens were developing compressive strength slower than the control mix. The reason is that the pozzolan reaction in concrete mixtures occurs slowly, fly-ash concrete achieves significant improvement in its mechanical properties at later ages, the samples react to makes a denser form of C-S-H gel: $mCa(OH)_2 + nSiO_2 + pH_2O \rightarrow mCaO \cdot nSiO_2 \cdot (m+p)H_2O$. After 7 days of curing, the compressive strength for the samples M5, M4, M3, M2, M12, M7, M6, and M10, with replacement levels at 20–30 % for fly ash and 5–2.5 % for SF, achieved strength values superior (by 2.5–18 %) to those of control mix M0 (71.101 MPa). On the other hand, samples M11, M7, M9, and M13 with 40 % fly ash and SF in the range between 5 and 12.5 % obtained compressive strength similar to the previous findings [48–49]. As seen in Fig. 1, there is a slight increase in the compressive strength of concrete mortars kept in water after 28 days of curing concretes when using 20 % fly ash incorporated with different replacement levels of SF from 5 to 12.5 % corresponding to samples M2, M3, M4, M5. Increasing fly ash content in the mixture up to 30 % in combination with SF replacement rates of 5–12.5 %, which corresponds to mixtures M10, M6, M7, and M12, showed compressive strength higher than or similar to control mix M0. On the contrary, however, the addition of up to 40 % FA to the mixture containing SF with different replacement rates (5–12.5 %), indicated a downward trend for strength in samples M11, M8, M9, and M13. Notice that there's only one mix (sample M9) that obtained strength higher than the control mix without any additional materials (M0). This demonstrates that the action of micro fillers as well as an increase in the pozzolans reaction of SF and FA particles still do not offset the dilution effect in adhesive cement at the age of 28 days.

The diagram in Fig. 3 shows the average flexural strength of different HPC mixes after 28-day curing. The control mix had a flexural strength of 8.8 MPa, while the group of samples M3, M4, M7, M9, and M5 modified by the industrial by-product waste materials had flexural strength values higher than that of the control mixture by up to 3.4–5.2 %. Besides, the remaining specimens also had the flexural strength value approximately equal to the control mix. The addition of same materials improved the interface characteristics between the bonding layer and aggregate, leading to increased interface adhesion, and hence ameliorating the bending resistance of the concrete. On the other hand, Fig. 3 shows that the splitting tensile strength values obtained were up to 7.4 % greater than the control mix in the mixtures using a combination of 10 % SF plus 30–40 % FA or 20 % FA plus 7.5/12.5 % SF. Conversely, some mixtures showed a drop in tensile strength (about 6.1 %) at the age of 28 days compared with the control mix, as for example, in mixtures with silica fume at levels of 5–12.5 % combined with 40 % content of fly ash partially replacing cement in the mixture.

The results of mass loss and compressive strength for concrete samples during the immersion period of 14 months in marine and saline-alkaline media are summarized in Table 5, as well as in Fig. 2. Based on the data obtained, simultaneous examination of the surface of the experimental samples as shown in

Fig. 4 indicated that the surface of the samples began to show signs of corrosion, e. g., fine aggregate emerging, discoloration, salt agglomeration; marine creatures sticking, etc.

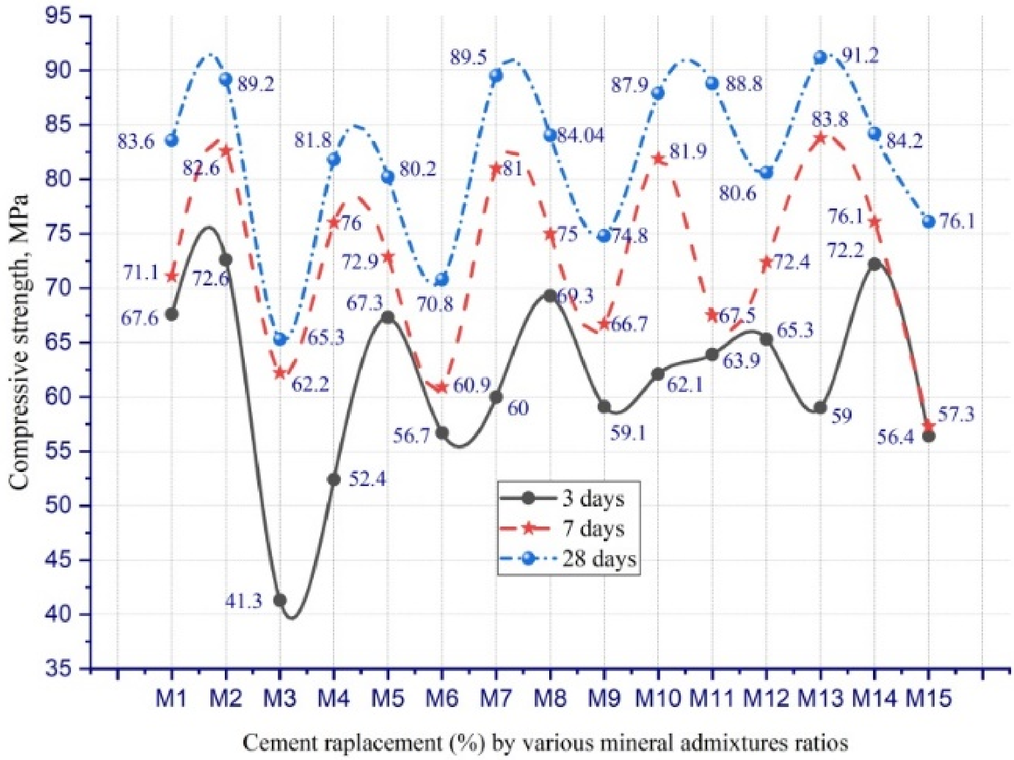

Figure 1. Compressive strength of HPC mixtures at different ages.

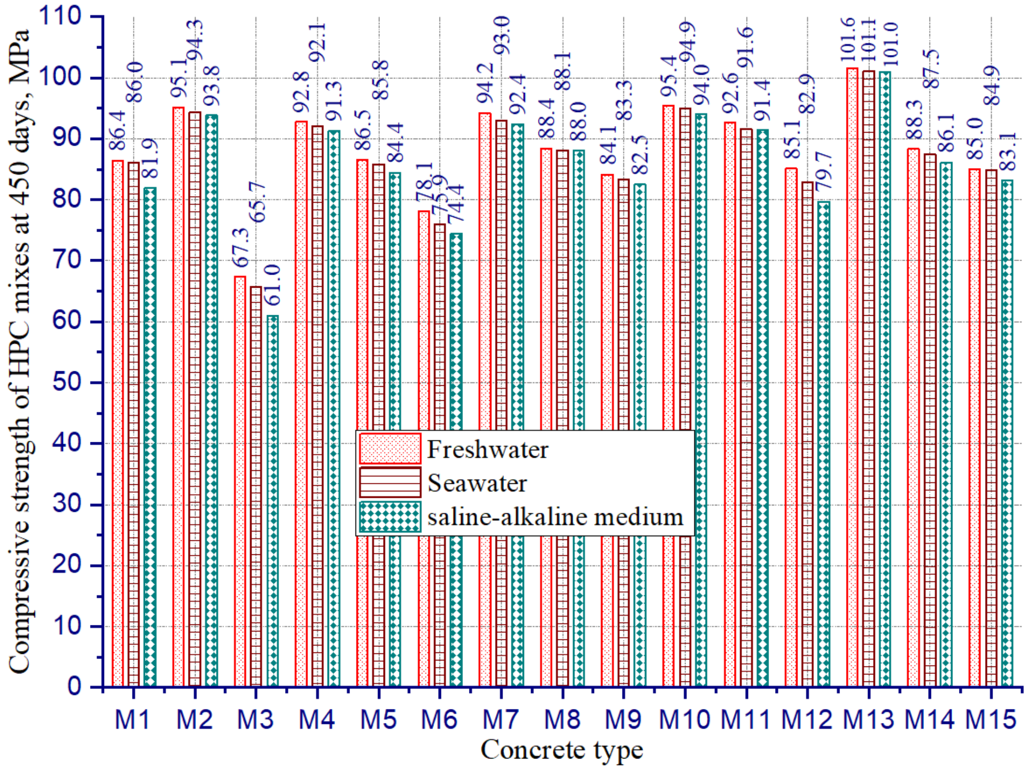

Figure 2. Compressive strength of HPC mixtures at 450 days in different environments.

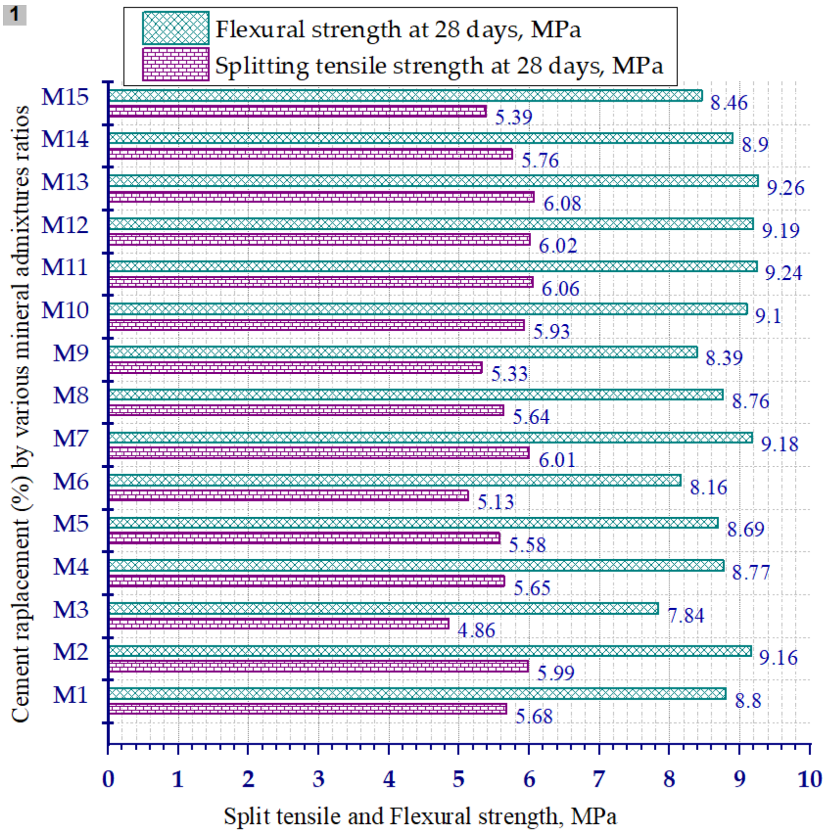

Figure 3. Flexural, splitting tensile strength of HPC mix at 28 days.

The $PC_{SR}40$ sample (M0) in the saline-alkaline medium after 450 days exhibited strong damage followed by high mass loss of about 2.1 % and compressive strength loss at 5.1 %, which was higher than in seawater environment (strength loss 0.4 %). Sample M1 showed similar compressive strength loss at 9.4 % and degradation of physical-mechanical properties, so further investigation was stopped. Cement content of 45–52.5 % replaced by 40 % fly ash and from 5 to 12.5 % SF in samples M11, M7, M9, and M13 showed compressive strength loss at 1.9–6.4 % and mass loss of about 0.3–0.5 %. In contrast, cement content of 25–32.5 % replaced by 20 % fly ash and from 5 to 12.5 % SF in samples M2, M3, M4, and M5 showed compressive strength loss at 0.6–1.9 % and mass loss of about 0.1–0.4 %. At the same time, cement content of 35–42.5 % replaced by 30 % fly ash and from 5 to 12.5 % SF in samples M10, M6, M7, and M12 showed compressive strength loss at 0.5–2.4 % and mass loss of about 0.1–0.3 %. All these mixtures demonstrated that weight loss, as well as strength, are much higher than in the seawater environment. We could conclude that during this period, different corrosion resistance in seawater and saline-alkaline media is obviously the consequence of the applied FA, SF, and Qp fillers. The samples corroded in varying degrees depending on different percentages of active mineral admixture ratios used to replace the cement content in concrete.

Based on the results of the analysis of environmental composition, the results of the evaluation of the corrosive process products, the authors found that concrete in saline-alkaline medium was corroded by acid corrosion mechanism in the most basic corrosion form.

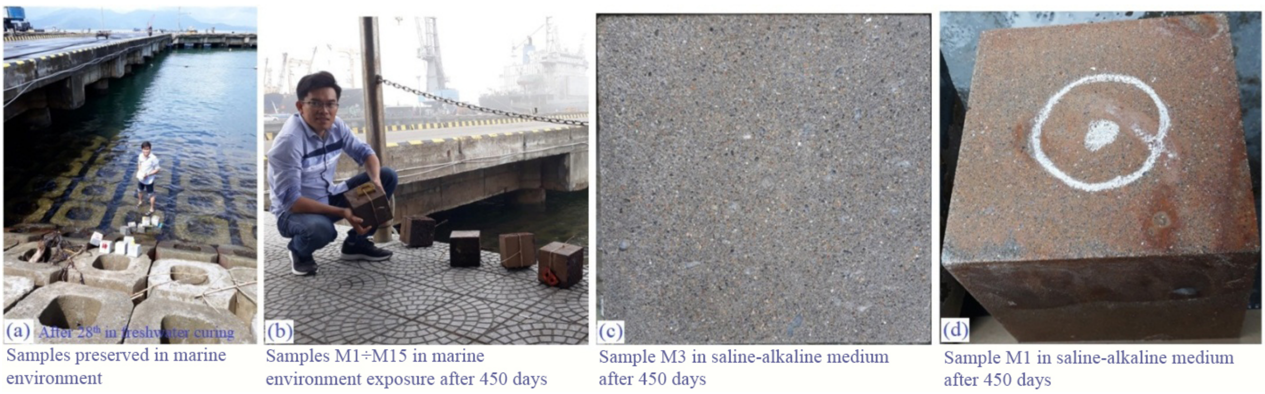

Figure 4. Effect of curing methods: (a, b) seawater curing and (c, d) saline-alkaline curing.

Permeability is a measure of the ease with which the substances are transported due to a pressure differential, while absorptivity and absorption-to-porosity are measures of the absorption characteristics of concrete. The permeability of concrete is a function of the w/b ratios, aggregates particles size, pore size, and its distribution in the mix. The permeability of hardened cement paste greatly affects the durability of concrete and in turn, is strongly affected by the pore structure. The pore structure is formed during the hydration process. The void spaces between the cement particles start to fill up with hydration products. The w/b ratio and the degree of hydration determine the total capillary porosity. In general, the capillary porosity rises or drops as the w/b ratio rises or reduces. In addition, adding a supplementary cementitious material finer than cement such as FA and SF (incorporated with a reasonable dosage of superplasticizer) to fill into the voids can significantly increase the packing density of the cementitious materials leading to low permeability of the concrete. Therefore, blending Portland cement with pozzolanic materials has become an increasingly accepted practice in the construction of structures exposed to harsh environments such as offshore structures, highway bridges, tunnels, sewage pipes, and structures for wastes containing toxic chemicals and radioactive elements. According to TCVN 3116- 2007[14], cylindrical samples are used to check the water permeability, correspondent to GOST 12730.5-2018[15]. As expected, water permeability values decreased (i.e., the concrete became more impervious) with increasing age due to the improvement on concrete microstructure, resulting from the increased amount of the C-S-H phase.

Table 6. Water permeability and water absorption of concrete at the 28th day

Mix N^o	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15
Water permeability, $K_{t*}10^{-11}$ cm/sec	1.60	1.18	3.16	1.21	1.33	2.6	1.13	1.21	1.98	1.1	1.03	1.09	1.01	1.08	1.63
Concrete grades for watertightness	W16 – W20														
Water absorption in 24 hours, %	2.50	2.39	3.23	2.52	2.57	3.01	2.38	2.53	2.86	2.43	2.19	2.33	2.03	2.54	2.82

An economic analysis was carried out for all the mixes. The unit price includes the costs of all ingredients necessary for producing the HPC mixtures, excluding the transportation costs. For this, the material prices used were as follows: Cement $PC_{SR}40$ – 1.66 vnd/kg ; Silica Fume Sikacrete® PP1 – 12.00 vnd/kg, 86 % higher unit price than the cement; class F fly ash – 500.00 vnd/ton, 69 % lower unit price than the cement; coarse aggregate – 320.00 vnd/m^3; fine aggregate – 400.00 vnd/m^3; quartz powder – 600.00 vnd/ton; potable water – 16.72 vnd/m^3; and Sika®ViscoCrete®151 – 44.00 vnd/l. The exchange rate was 1USD = 23.23 VND. The material cost of the concrete per cubic meter for each mix are presented in Table 4. These costs apply to locally available materials in Thua Thien Hue province, Vietnam, in 2019. It can be noted from the figures in Table 4 that the control mix has the lowest price, but as the SF content added was gradually rising, so were the prices of the concrete. Among the samples that have the compression strength greater than or equal to the control mixture (86.5 MPa after 450 days), sample M5 (12.5 % SF + 20 % FA) mix had the maximum strength attained (101.6 MPa), while also having the highest material price (103.04 \$/1m^3). The average cost per strength was 0.87 \$/m^3/MPa for the control mixture; 0.91 \$/m^3/MPa corresponds to M1 mixture; 0.96 \$/m^3/MPa to M10, M3, and M6 mixtures; 1.0 \$/m^3/MPa for the designed M8, M4, M7, M5 mixtures, respectively; and 1.13\$/m^3/MPa corresponds to M12 mixture.

4. Conclusion

Based on the observations and the experimental studies through the results achieved in this study, the following conclusions may be drawn.

The research results are consistent with the results previously obtained by other authors.

The authors developed a method of HPC mix proportioning for a target strength range of approximately 80 MPa to suit Vietnamese climatic conditions by using locally available materials. Moreover, part of cement content in mixes was replaced by industrial by-product waste materials such as FA and SF with dosages ranging within 25–55 %, but still assuring the total binder fixed constant of 550 kg/m^3. The results confirmed that at the age of 56 days, almost all concrete mixes designed in the above research attained strength ranging from 85 to 105 MPa, and their physical properties continued to grow at older ages.

It was established that high-performance concrete with respect to strength and durability can be produced from mixtures with a water-binder ratio at 0.35 and cementitious material content of at least 550 kg/m^3, including 20 to 40 % fly ash and 5 to 12.5 % silica fume. The results of the experiment showed that almost all the mixes containing SF content at 10 % reached the highest physical properties at all ages.

Therefore, 10 % is the optimum replacement content of SF in concrete mixtures when combined with 20–40 % FA content.

References

1. Hoff, G.C. Utilization of high-strength concrete in North America. Proceeding of the Third International on Utilization of High-Strength Concrete in Lillehammer. Oslo, 1993. Pp. 28–36.
2. Holand, I. High-strength concrete in Norway – Utilization and Research. Proceeding of the Third International on Utilization of High-Strength Concrete. Oslo, 1993, Pp. 68–79.
3. Pierre-Claude Aitcin and Moussa Baalbaki. Canadian Experience in Producing and testing HPC, ACI SP-159, 1996. Pp. 295–308.
4. De Larrard. A survey of recent research performed in French “LPC” Network on High-Performance Concrete. The Third International on Utilization of High-Strength Concrete. Norwegian Concrete Association, Oslo, 1993, Pp. 57–67.
5. Sicard, V., Pons, G. Bétons à hautes performances: quelques phénomènes différés liés à leur desiccation [High-performance concretes: some phenomena in relation to desiccation]. Materials and Structures. 1992. 25(10). Pp. 591–597. DOI: 10.1007/bf02472227
6. Potter, R.J., Guirguis, S. High-strength concrete in Australia. The Third International on Utilization of High strength Concrete in Lillehammer, Norway. Oslo, 1993, Pp. 581–589.
7. König, G. Utilization of High-strength concrete in Germany. Proceeding of The Third International on Utilization of High strength Concrete in Lillehammer, Norway. Oslo, 1993. Pp. 45–56.
8. Aoyama, H., Murato, T., Hiraishi, H., Bessho, S. Outline of the Japanese National Project on Advanced Reinforced Concrete Buildings with High-Strength and High-Quality Materials. ACI SP-121. 1990. Pp. 21–31.
9. Shin, S.-W. High-strength concrete in Korea. Engineered Concrete Structures, Portland Cement Association, Skokie, IL. 1990. 3(2). Pp. 3–4.
10. Jinquam, Z., Qingchang, H. High strength concrete in China. Engineered Concrete Structures. Portland Cement Association. 1993. 6(2). Pp. 1–3.
11. Chern, J.C., Hwang, C.L., Tsai, T.H. Research and development of High-performance Concrete in Taiwan. Concrete International. 1995. 17(10). Pp. 71–77.
12. Russell, H.G. What is High Performance Concrete? Concrete Products Magazine. 1999. Pp. 121–22.
13. Bazhenov Y.M., Aleksandrova O.V., Nguyen D.V.Q., Bulgakov B.I. High-performance concrete produced with locally available materials in Vietnam. Stroitel’nye Materialy [Construction Materials]. 2020. 3. Pp. 32–38. (rus) DOI: 10.31659/0585-430X-2020-779-3-32-38
14. Bazhenov, Y.M., Demyanova, V.S., Kalashnikov, V.I. Modifitsirovannyye vysokokachestvennyye betony [Modified high-quality concrete]. Publishing House of Association of construction universities (book). Moscow, 2006. 368 p. (rus)
15. Bazhenov Y.M., Nguyen, V.Q., Aleksandrova O.V. Effect of quartz powder and mineral admixtures on the properties of high-performance concrete. Vestnik MGSU. 2019. 14(1). Pp. 102–117. DOI: 10.22227/1997-0935.2019.1.102-117
16. Pulyaev, S., Pulyaev, I., Korovyakov, V., Sitkin, A. Research of hydration heat of Portland cement used in bridge construction of Kerch Strait. MATEC Web Conf. Building Materials. 2018. 251. 01036. DOI: 10.1051/matecconf/201825101036.
17. Pulyaev, I., Pulyaev, S. Effects of heat exchange features hardening concrete with environment on its heat physical properties. Mater. Today Proc. 2019. 19. Pp.1937–1940. DOI: 10.1016/j.matpr.2019.07.045
18. Shah, S.P., Ahmad, S.H. High Performance Concrete: Properties and Applications (book), Mc-Graw-Hill Inc. Pub., New York, 1994, 395 p.
19. Kumbhar, P.D., Pranesh Murnal. ”Effect of Humidity and Temperature on Properties of High Performance Concrete”, New Building Materials and Construction World. 2011. 16(11). Pp. 204–10.
20. Drzymała, T., Jackiewicz-Rek, W., Tomaszewski, M., Kuś, A., Gałaj, J., Šukys, R. Effects of high temperature on the properties of High-performance concrete (HPC). Procedia Engineering. 2017. 172. Pp. 256–263. DOI: 10.1016/j.proeng.2017.02.108
21. Benli. A. Mechanical and durability properties of self-compacting mortars containing binary and ternary mixes of fly ash and silica fume. Structural Concrete. International Federation for Structural Concrete. 2019. Pp. 1–13. DOI: 10.1002/suco.201800302
22. Karthikeyan, G., Balaji, M., Adarsh R. Pai, Muthu Krishnan, A. High-Performance Concrete (HPC)—An Innovative Cement Concrete Mix Design to Increase the Life Span of Structures. Sustainable Construction and Building Materials. 2018. Pp. 189–199. DOI: 10.1007/978-981-13-3317-0_17
23. Bilek, V., Pytlik D., Bambuchova, M. High Performance Concrete with Ternary Binders. Key Engineering Materials. 2018. 761. Pp. 120–123. DOI: 10.4028/www.scientific.net/KEM.761.120
24. Alsalman, A., Dang, C.N., Hale, M.W. Development of Ultra-High Performance Concrete With Locally Available Materials. Journal of Construction and Building Materials. 2017. 133. Pp. 135–145. DOI: 10.1016/j.conbuildmat.2016.12.040
25. Benli, A., Turk, K., Ceren, K. Influence of Silica Fume and Class F Fly Ash on Mechanical and Rheological Properties and Freeze-Thaw Durability of Self-Compacting Mortars. Journal of Cold Regions Engineering. 2018. 32(3). DOI: 10.1061/(asce)cr.1943-5495.0000167
26. Singh, H., Thakur, S. Research on effect of silica fume and fly ash with partial replacement of cement and fine aggregate. International Journal of Civil Engineering and Technology (IJCIET). 2018. 9(8). Pp. 113–119.
27. Hajek, P. Advanced high-performance concrete structures – challenge for sustainable and resilient future. The 4th International Conference on Rehabilitation and Maintenance in Civil Engineering (ICRMCE 2018). MATEC Web of Conferences. 2018. 195. DOI: 10.1051/matecconf/201819501001
28. Hajek, P., Fiala. C. Advanced Concrete Structures for the Sustainable- and Resilient-Built Environment. ACI, Moscow, 2018. Pp. 69.1–69.8.
29. Osama, A.M., Omar, F.N. Compressive strength and stability of sustainable self-consolidating concrete containing fly ash, silica fume, and GGBS. Frontiers of Structural and Civil Engineering. 2017. 11(4). Pp. 406–411. DOI: 10.1007/s11709-016-0350-1
30. Chena, J.J., Ng, P.L., Li, L.G., Kwan, A.K.H. Production of High-performance Concrete by Addition of Fly Ash Microsphere and Condensed Silica Fume. Procedia Engineering. 2017. 172. Pp.165–171. DOI: 10.1016/j.proeng.2017.02.045

31. Sung, W. Y., Kwon, S.J., Jung, S.H. Analysis Technique for Autogenous Shrinkage in High Performance Concrete with Mineral and Chemical Admixtures. Construction and Building Materials. 2012. 34. Pp. 1–10. DOI: 10.1016/j.conbuildmat.2012.02.005
32. Elahi, A., Basheer, P.A.M., Nanukuttan, S.V., Khan, Q.U.Z. Mechanical and Durability Properties of High-performance Concretes Containing Supplementary Cementitious Materials. Construction and Building Materials. 2010. 24(3). Pp. 292–299. DOI: 10.1016/j.conbuildmat.2009.08.045
33. Pham, H.H., Nguyen, V.T. High performance concrete used for marine gravity concrete works. The 3rd ACF International Conference, Vietnam, 2008. Pp. 598–606.
34. El Shikh, M.M.Y. Economy of Using High Performance Concrete in Columns. 33rd Conference on Our World in Concrete & Structures. Singapore, 2008 Pp. 1–8.
35. Arunachalam, K., Gopalakrishnan, R. "Experimental Investigation on High Performance Fly Ash Concrete in Normal and Aggressive Environment," 29th Conference on Our World in Concrete & Structures. Singapore, 2004. Pp. 181–188.
36. Khan, M.I. Permeation of High performance concrete. Journal of Materials in Civil Engineering. 2003. 15(1). Pp. 84–92. DOI: 10.1061/(ASCE)0899-1561(2003)15:1(84)
37. Zain, M., Radin, S. Physical properties of High-performance concrete with admixtures exposed to a medium temperature range 20°C to 50°C. Cement and Concrete Research. 2000. 30(8). Pp. 1283–1287. DOI: 10.1016/S0008-8846(00)00294-5
38. Tamimi, A.K. High-performance concrete mix for an optimum protection in acidic conditions. Materials and Structures. 1997. 30(3). Pp. 188–191. DOI: 10.1007/BF02486392
39. Kwan, A.K.H., Chen, J.J. Adding fly ash microsphere to improve packing density, flowability and strength of cement paste. Powder Technology. 2013. 234. Pp. 19–25. DOI: 10.1016/j.powtec.2012.09.016
40. Ministry of Natural Resources and Environment (Vietnam). Climate change and Sea level rise scenarios for Viet Nam – Ha Noi. 2016. 188 p.
41. Scott, A., Kulp, H. Strauss Benjamin. New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. NATURE COMMUNICATIONS. 2019. 12 p. DOI: 10.1038/s41467-019-12808-z
42. Khuong, V.H., Le M. Acid acid water causes corrosion of reinforced concrete for irrigation works in the Mekong Delta. Journal of Science. Technology. Water Resources and Environment. 2009. 26.
43. Khuong, V.H. Evaluation of concrete strength on irrigation works in the Mekong Delta. Journal of Construction Science and Technology. Hanoi. 2019. 9.
44. Jae, H.K., Nagy, N., Surendra, P.S. Effect of powder materials on the rheology and formwork pressure of self-consolidating concrete. Cement and Concrete Composites. 2012. 34 (6). Pp. 746–753. DOI: 10.1016/j.cemconcomp.2012.02.016
45. Alireza Kashani, R.S., Nicolas, G.G., Qiao, J.S.V. Deventer, John L.Provis, Modelling the yield stress of ternary cement-slag-fly ash pastes based on particle size distribution. Powder Technology. 2014. 266. Pp. 203–209. DOI: 10.1016/j.powtec.2014.06.041
46. Dale, P. B., Ferraris, C.F., Galler, M.A., Hansen, A.S., Guynn, J.M. Influence of particle size distributions on yield stress and viscosity of cement fly ash pastes. Cement and Concrete Research. 2012. 42(2). Pp. 404–409. DOI: 10.1016/j.cemconres.2011.11.006
47. Lee, C.Y., Lee, H.K., Lee, K.M. Strength and microstructural characteristics of chemically activated fly ash-cement systems. Cement and Concrete Research. 2003. Vol. 33 (3). Pp. 425–431. DOI: 10.1016/S0008-8846(02)00973-0
48. Shaikh, F., Supit, S. Compressive strength and durability properties of high volume fly ash concretes containing ultrafine fly ash. Construction and Building Materials. 2015. 82. Pp. 192-205. DOI: 10.1016/j.conbuildmat.2015.02.068
49. Saha, A.K., Sarker, P.K. Sustainable use of ferronickel slag fine aggregate and fly ash in structural concrete: Mechanical properties and leaching study. Journal of Cleaner Production. 2017. 162. Pp. 438–448. DOI: 10.1016/j.jclepro.2017.06.035

Information about authors:

***Boris Bulgakov**, PhD in Technical Science*
ORCID: https://orcid.org/0000-0002-4737-8524
E-mail: fakultetst@mail.ru

***Vinh Quang Nguyen**,*
ORCID: https://orcid.org/0000-0001-5840-5279
E-mail: ndvquang@hueic.edu.vn

***Olga Aleksandrova**, PhD in Technical Science*
ORCID: https://orcid.org/0000-0003-1791-8515
E-mail: aleks_olvl@mail.ru

***Oksana Larsen**, PhD in Technical Science*
ORCID: https://orcid.org/0000-0002-9612-7190
E-mail: larsen.oksana@mail.ru

***Nadezhda Galtseva**, PhD in Technical Science*
ORCID: https://orcid.org/0000-0003-2014-6739
E-mail: gslcevanadezda@mail.ru

Received 23.11.2020. Approved after reviewing 13.07.2022. Accepted 22.07.2022.