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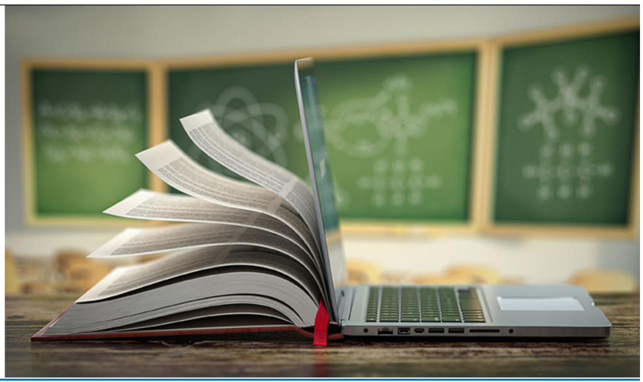

The Properties of High-strength Concrete with High Volume of Natural Pozzolan

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Abstract. This paper presents the properties of high-strength concrete containing a high volume of N-class natural pozzolan sourced from the Northern part of Vietnam. Based on the conducted studies' results showed that the mechanical properties of the natural pozzolan concrete were generally lower than those of control concrete. However, with effects combined of natural pozzolan and SR-5000F superplasticizer on the microstructure of concrete, mechanical properties of high-strength concrete increases with the amount of natural pozzolan from 10 to 20% by mass of cement, then descends. In addition, the maximum temperature of both conventional and High-strength concrete specimens significantly decreases with the increasing content of natural pozzolan. Furthermore, the relationship between compressive and flexural strength, modulus of elasticity and compressive strength of heavyweight concrete specimens are also determined in this investigation.

1. Introduction

Nowadays, binders containing Portland cement with industrial wastes, silica fume, or a natural pozzolan are widely used in high-performance concrete for High-Rise Construction [1, 2] or in roller-compacted concrete for pavement [3] and dam [4]. The use of waste materials, including slags and ashes, building rubble, and sewage sludge as additives in concrete and mortar build is not only environmental protection or environmental sanitation issue but also modifies the properties of concrete with improvements in workability, strength, and shrinkage [5, 6]. Furthermore, in previous investigations [7-9] were presented using active mineral additives to reduce the heat of hydration of cement in concrete types to different extents.

However, most building materials, containing active mineral additives especially natural pozzolans (PU), tend to increase the mixing water requirement for conventional concrete mixes and lower the rate of strength development. Therefore, for structural applications, PU proportion in concrete mixtures is generally limited to 30% or less by weight of ordinary Portland cement (OPC) [10, 11].

Studies [12, 13] have shown that high-performance concrete mixtures containing over 50% of fly ash by weight of cement can be produced with the help of superplasticizer admixtures. Furthermore, in the research [14] were prepared the concrete mixtures made with 50 and 70% replacement of OPC with fly ash. Particularly, the blended cements with 55% mas of PU are produced in a laboratory [15]. Published literature contains no reports of similar studies with high-strength concrete containing a high volume of PU. One of the objectives of this work is to fulfil this need.

In Vietnam, the PU locally available in mines in the Northern mountains is mainly Class N (by standard ASTM 618-17) and been used as an additive for both cement and concrete with very good quality and stability.

The purpose of the current investigation was to determine the properties of High-strength Concrete containing 50% volume of natural pozzolan of Vietnam replacement of Portland cement. The relationships between strength properties and modulus of elasticity in the different proportion mixtures of tested concrete samples are determined. In addition, the estimation of maximum temperature in the mixture tested is also discussed by a quick method, which proposed by the Portland Cement Association's design.

2. Research programs

2.1. The properties of Material

a). The coarse aggregate in the preparation of High-strength and conventional concrete specimens for this study was used Vietnam crushed limestone (CL) with the particle sizes of 5÷20 mm (D_{max} = 20 mm). On the other hand, the fine aggregate in the both concrete series was used Red River quartz sand (QS) (Vietnam) with fineness modulus M_k = 3.0. The physical properties of both the CL and QS are shown in Table 1.

Table 1. The physical properties of CL and QS in this test

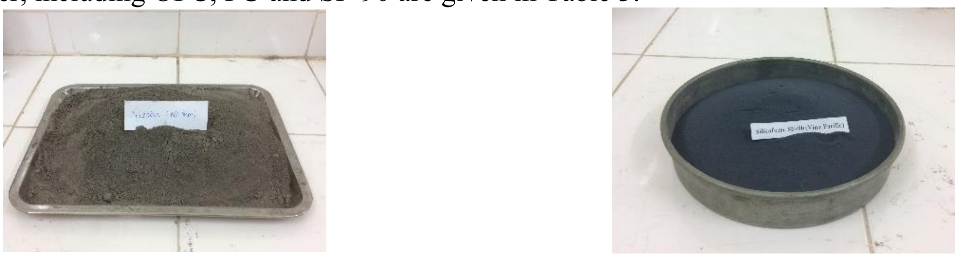
Aggregate type	Size (mm)	Loose density (kg/m^3)	Dry density (kg/m^3)	Saturated density (kg/m^3)	Water absorption (%)
CL	5 ÷ 20	1550	2650	2690	0.4
QS	0.15 ÷ 5	1660	2650	2690	0.6

b) The ordinary Portland cement (OPC) 40-Grade was used, manufactured at "Tam Diep" factory (Vietnam) with its specific weight of 3.15 g/cm^3. The tested results of physic-mechanical properties of OPC are shown in Table 2.

Table 2. The physical properties of OPC

Specific weight (g/cm^3)	Retained content on sieve 0.09 mm (%)	Surface area (cm^2/g)	Time of setting (min)		Compressive strength (MPa)			Standard consistency (%)
			Initial	Final	3-d	7-d	28-d	
3.15	5.5	3640	120	360	27.4	35.3	45.8	29.5

c) The active mineral additives used include natural pozzolan (PU) of "Gia Quy" in Vietnam (refer Figure 1-a) and SF-90 silica-fume (SF-90) (Vina-Pacific co., Ltd., Vietnam) (Figure 1-b). The specific weight, dry density of natural porous state and average particle size are, respectively, 2.81 g/cm^3, 980 kg/m^3 and 6.67 µm for PU and 2.25 g/cm^3, 760 kg/m^3 and 0.243 µm for SF-90. In this case, PU, SF-90 and OPC were used as a binder in both test series. The experimental results of chemical compositions of the binder, including OPC, PU and SF-90 are given in Table 3.



(a) (b)

Figure 1. The active mineral additives including (a) - natural pozzolan and (b) - silica fume SF-90

Table 3. Chemical properties of OPC, SF-90 and PU

Materials	Average chemical composition (%)							
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Loss on ignition	Other
OPC	19.8	4.1	5.4	61.9	2.8	3.2	2.5	0.3
SF-90	91.65	2.25	2.47	0.51	-	-	2.54	0.58
PU	48.7	22.3	12.5	3.5	4.7	1.5	3.2	3.6

ed) The superplasticizer admixture SR-5000F (SP) "SilkRoad" of Hanoi-Korea in Vietnam with its specific gravity of 1.1 g/cm^3 at temperature of 25°C was used to increase the concrete flow or to reduce the ratios of water to cement thus increasing the material strength of concrete specimens.

e) Local tap water (W) was used for both mixing raw materials and curing of the test patterns in this study.

2.2. Methods of test

1. The calculation method of the compositions of concrete mixture was applied in accordance with Vietnamese standard TCVN 9382 – 12 for the conventional concrete and with standard ACI 211.4R-2008 (American Concrete Institute) for the High-strength concrete.

2. The workability of fresh concrete is determined by the standard slump cone with dimensions of 100x200x300 mm by Russian standard GOST 10181-2014.

3. The compressive - flexural strength of the both concrete series were determined by GOST 10180-2012 (Russian standard). The strength properties of High-strength and conventional concrete specimens were tested at the different ages (3, 7, 14 and 28-day).

4. The concrete modulus of elasticity is determined by ASTM C469/C469M -14.

In this work, all the test patterns of concrete series were demoded after 24 hours right after casting and subjected to standard maintenance Treatment (temperature from 20 ^{o}C to 25^{o}C and with high air humidity above 90%) until the age of design (Figure 2).

The test was performed using a "Controls Advantest 9" computer-controlled compression system with a constant loading rate of 1500 N/s in order to keep the loading rate to a minimum rate in the processing test of concrete patterns (Figure 3).

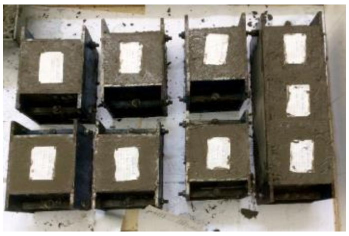


Figure 2. Experimental concrete specimens

Figure 3. Testing of specimen under compression

5. On the other hand, in the investigation the estimation of maximum temperature (T_{max}) in the both High-strength and conventional concrete containing PU is determined by a quick method of the Portland Cement Association's design and control of concrete mixtures. The Portland Cement Association's (PCA) [16] design and control of tested concrete mixtures gives a quick method for estimating the T_{max} developed in concrete members. This method calculates the T_{max} rise of the concrete mixture when the Portland cement content is in the range of 300 to 600 kg/m^3. According to ACI committee 207 [17] suggests that modification to account for supplementary cementitious materials can be made by presuming that they liberate approximately half of the amount of heat of cement for a given mass. According to the PCA, in concrete T_{max} is determined by equation (1) for concrete mixtures containing supplementary cementitious materials as PU, SF-90, slags and ashes, building rubble, and sewage sludge.

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$$T_{\max} = T_i + (12\frac{W_{Cement}}{100}) + (6\frac{W_{scm}}{100}) \quad (1)$$

where: T_i - the temperature of concrete placement (°C), in this study for Vietnam T_i = 25°C;
W_{cement} - the content of cement in 1 m^3 concrete mixture (kg);
W_{scm} - the supplementary cementitious materials content in 1 m^3 concrete (kg).

3. Results and Discussion

3.1. Mixture Proportioning

3.1.1. For the conventional concrete (CC).

a). The fresh concrete effect on workability is determined by the slump of standard cone in the range of 9 ÷ 15 cm.

b). The target mean compressive strength was above 40 MPa for the mixture with 100% content of OPC. The compressive strength of test is determined by using cube patterns with dimensions of 150x150x150 mm at the ages of 28-day of normal curing.

c). The mix proportion of conventional concrete was done as per the Vietnamese standard TCVN 9382 – 2012 [18]. The water- binder ratio ($\frac{W}{BID}$) was kept constant as 0.46.

3.1.2. For the High-strength concrete (HSC).

a). The workability of concrete mixture is determined by the slump of standard cone of 9 ÷ 15 cm.

b). The average value of compressive strength was 70 MPa for the High-strength concrete specimens with 100% Portland cement.

c). Using silica fume to replace 10% of mass cement in concrete mixture [2, 11].

d). The mix proportion of High-strength concrete was done as per the standard ACI 211.4R-2008 (American Concrete Institute). In case of the investigation, the $\frac{W}{BID}$ = 0.33.

e). The superplasticizer "SR-5000F SilkRoad" is equally to 1.0% by mass of binder (Binder - BID = PC + PU + SF) [11].

In addition, using natural pozzolan to replace from 10% to 50% of mass Portland cement in the both CC and HSC mixtures. Besides, relative volume of entrapped air is 2.5% in 1 m^3 of the tested concretes.

The all concrete mixture compositions used in this study and its workability were shown in Table 4.

Table 4. Mix compositions and slump of fresh concrete

No.	Compositions of concrete mixture	$\frac{W}{BID}$	Concrete mixture (kg/m^3)							Slump (cm)
			OPC	PU	QS	CL	W	SP	SF-90	
CC-1	100% OPC	0.46	490	0	545	1108	225	-	-	14
CC-2	90% OPC + 10% PU		441	49	535	1108	225	-	-	14.5
CC-3	80% OPC + 20% PU		392	98	535	1108	225	-	-	14
CC-4	70% OPC + 30% PU		377	113	535	1108	225	-	-	13
CC-5	60% OPC + 40% PU		294	196	535	1108	225	-	-	13
CC-6	50% OPC + 50% PU		245	245	535	1108	225	-	-	13
HSC-1	100% OPC	0.33	485	0	495	1166	176	5.34	48.5	15
HSC-2	90% OPC + 10% PU		445	44.5	482	1166	176	5.34	44.5	15
HSC-3	80% OPC + 20% PU		411	82.2	470	1166	176	5.34	41.1	15
HSC-4	70% OPC + 30% PU		381	114.3	459	1166	176	5.34	38.1	15
HSC-5	60% OPC + 40% PU		356	142.4	451	1166	176	5.34	35.6	14
HSC-6	50% OPC + 50% PU		334	167	443	1166	176	5.34	33.4	14

Data presented in Table 5 was shown that the addition of natural pozzolan only slightly decreased the workability of mixtures in both CC and HSC. This could be explained by the natural pozzolan has tended to increase the mixing water requirement for tested concrete. Especially in HSC mixtures with the help of SR-5000F superplasticizer admixture, their workability was in the range of 14 cm to 15 cm. The results of this investigation, similar to the results found in previous studies [14, 15]

3.2. Effect of natural pozzolan on the properties of tested concrete

The experimental results of all concrete specimens used in this study are presented in Tables 5 and 6.

Table 5. Compressive strength development of concrete at different ages

No.	Compressive strength (f_{cs}) at different ages									
	MPa					%				
	3-d	7-d	14-d	28-d	56-d	3-d	7-d	14-d	28-d	56-d
CC-1	24.8	34	41.5	43.8	51.5	100	100	100	100	100
CC-2	24	33.1	40.7	43	51	96.77	97.35	98.07	98.17	99.03
CC-3	20.2	30.5	34.7	38.7	45.6	81.45	89.71	83.61	88.36	88.54
CC-4	16.9	23.2	33.7	37.1	41.3	68.15	68.24	81.20	84.70	80.19
CC-5	14.5	20.4	28.1	32.6	40.5	58.47	60.00	67.71	74.43	78.64
CC-6	12.9	17.8	25.8	28.4	32.4	52.02	52.35	62.17	64.84	62.91
HSC-1	35.7	50.6	64.9	71.3	74.8	100	100	100	100	100
HSC-2	38.4	55.4	69.4	73.8	77.1	107.56	109.49	137.15	145.85	152.37
HSC-3	44.5	57.1	70.4	74.1	77.9	124.65	112.85	139.13	146.44	153.95
HSC-4	40.4	51.8	65.2	70.9	73.7	113.17	102.37	128.85	140.12	145.65
HSC-5	30.9	42.2	60.2	68.4	72.4	86.55	83.40	118.97	135.18	143.08
HSC-6	24.5	36.4	43.8	48.2	53.5	68.63	71.94	86.56	95.26	105.73

Table 6. Properties of tested concrete

No.	Flexural strength (f_{fs}) at the age of 28-day (MPa)	Elasticity modulus (E) of concrete (MPa)	Maximum temperature (^oC)
CC-1	3.45	30100	83.8
CC-2	3.37	29510	80.9
CC-3	3.10	28605	77.9
CC-4	3.05	27556	77.0
CC-5	2.58	26100	72.0
CC-6	2.40	24108	69.1
HSC-1	5.58	37645	86.1
HSC-2	5.51	37556	83.7
HSC-3	6.05	37870	81.7
HSC-4	5.36	37240	79.9
HSC-5	5.30	35475	78.4
HSC-6	4.05	32450	77.1

The experimental results presented that the compressive and flexural strength values of the tested concrete samples were, respectively, in the range of 28.4 ÷ 74.1 MPa and 2.40 ÷ 6.05 MPa at 28 days curing time, while at this age, the modulus of elasticity values was in the range of 24108 ÷ 37870 MPa. With effects combined of natural pozzolan and SR-5000F superplasticizer on microstructure of concrete, mechanical properties of HSC increases with the amount of natural pozzolan from 10 to 20% by mass of cement, then descends. These results of the study are presented in detail in Figures 4 and 5.

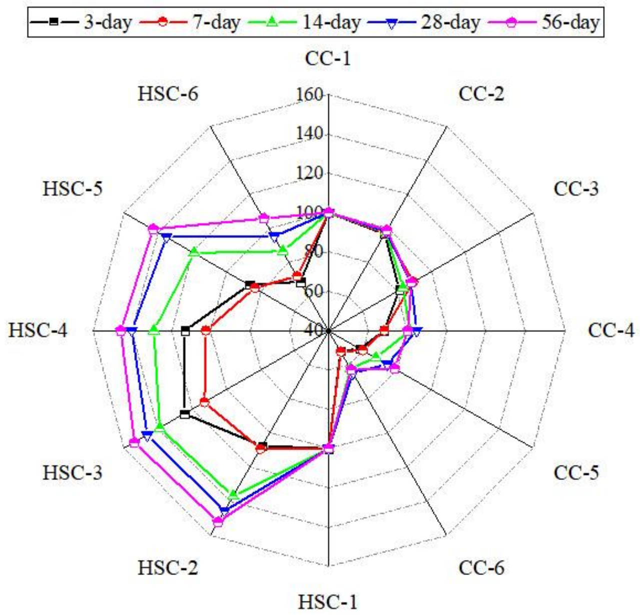

Figure 4. Ranking the development of compressive strength of tested concrete specimens at different ages

For clear observation, the speed of development in the compressive strength of the CC and HSC were presented in Figure 5.

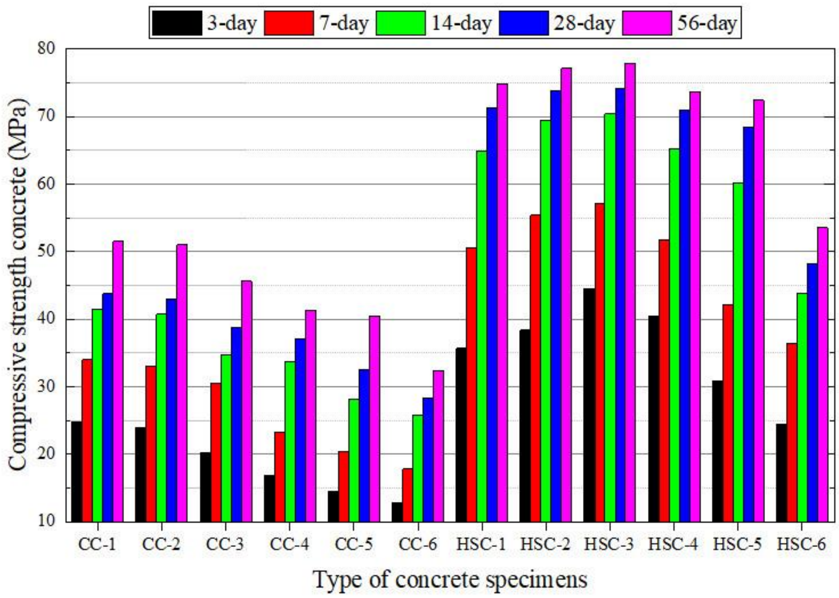

Figure 5. Compressive strength development of tested concrete specimens at different ages

3.3. Correlations

3.3.1. Compressive and flexural strength. The relations between the compressive strength - f_{cs} and the flexural strength - f_{fs} of the both conventional and High-strength concrete specimens are shown in Figure 6 and given in formulas (2) and (3).

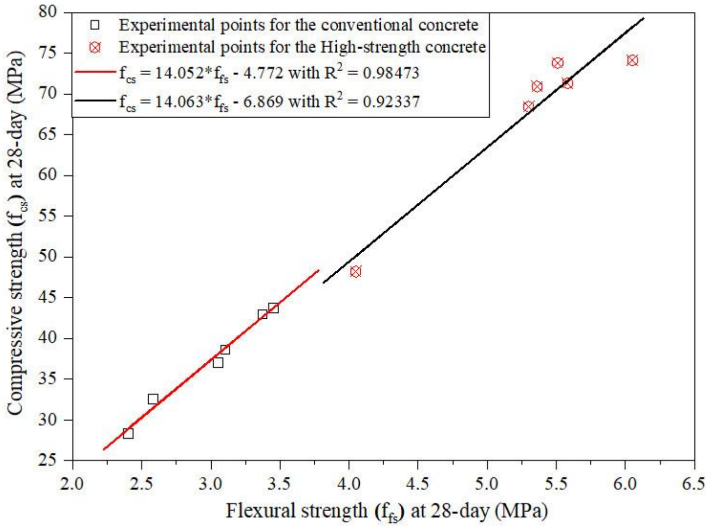

Figure 6. Correlation between compressive strength and flexural strength of CC and HSC specimens

- For CC samples: $f_{cs} = 14.052*f_{fs} - 4.772$ (MPa) with $R^2 = 0.98473$. (2)

- For HSC samples: $f_{cs} = 14.063*f_{fs} - 6.869$ (MPa) with $R^2 = 0.92337$. (3)

These relations suggest that although the strength of High-strength concrete is larger than that of the conventional concrete, the compressive - flexural strength ratio seems to be constant and is about 14.

3.3.2. Modulus of elasticity and compressive strength.

Figure 7 presents the relationship between modulus of elasticity – E and compressive strength - f_{cs} conventional and High-strength concrete.

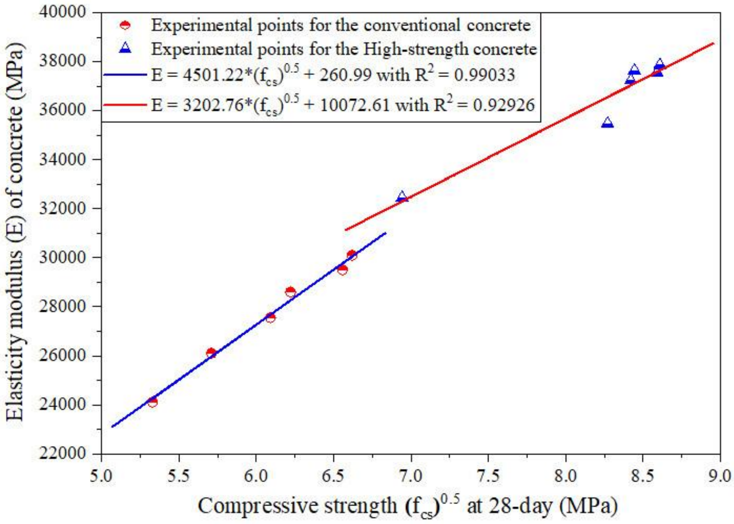

Figure 7. Correlation between modulus of elasticity and compressive strength of CC and HSC samples

In particular, in Figure 7 shown that the linear relationships between modulus of elasticity and compressive strength of CC and HSC with reasonable correlations coefficient (R^2 = 0.99033 and 0.92926) were obtained and shown in equations (4) and (5).

- For CC samples: $E = 4501.22*(f_{cs})^{0.5} + 260.99$ (MPa) with $R^2 = 0.99033$. (4)

- For HSC samples: $E = 3202.76*(f_{cs})^{0.5} + 10072.61$ (MPa) with $R^2 = 0.92926$. (5)

ACI 318-2005 suggested the relationship between the modulus of elasticity and compressive strength for all conventional concrete samples by equation (6):

$$E = 4730*(f_{cs})^{0.5} \text{ (MPa)} \quad (6)$$

Another standard ACI 363R-92 proposed the relationship between the modulus of elasticity and compressive strength for all high-strength concrete samples by equation (7):

$$E = 3300*(f_{cs})^{0.5} + 6.9 \text{ (MPa)} \quad (7)$$

These equations have shown that the suggested equations (4) and (5) underestimate the modulus of elasticity values for a given compressive strength, but not significantly.

The approximate PCA method is used to estimate the peak temperature rise in the tested concrete samples by Equation (1). The predicted maximum temperatures were displayed in Table 6, while the effect of natural pozzolan content on the maximum temperature of concrete specimens was shown in Figure 8.

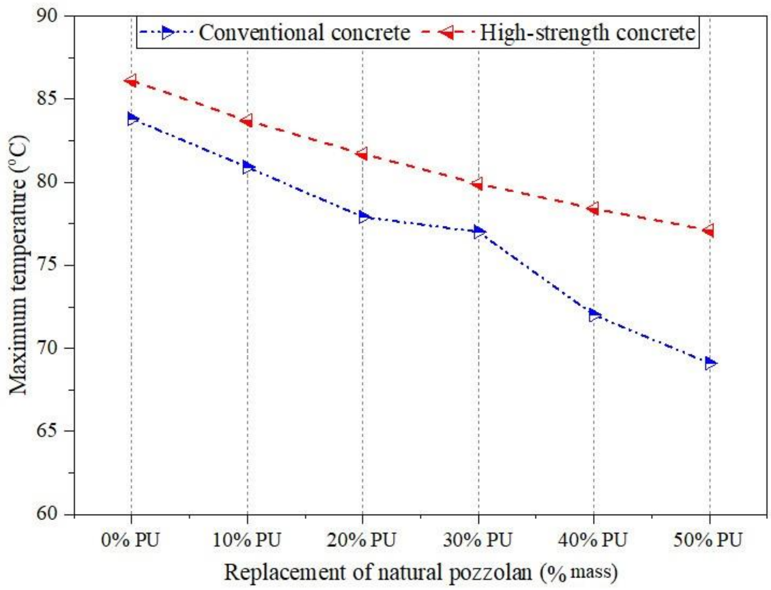

Figure 8. Effect of PU on the maximum temperature of tested concrete specimens

As expected, the maximum temperature of both CC and HSC specimens significantly decreases with increasing content of natural pozzolan. However, all samples of high-strength concrete have a temperature higher than the conventional concrete. This is caused by amounts of cement in the mixtures are much different.

4. Conclusions and future work

Based on the experimental results, the following conclusions are drawn on tested concrete samples containing high Volume of natural pozzolan used in this investigation:

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1. Compared to the reference concrete specimens, the mechanical properties of the concrete containing different content of PU were generally lower than those of control concrete. However, with effects combined of natural pozzolan and SR-5000F superplasticizer on the microstructure of concrete, mechanical properties of HSC increase with the amount of natural pozzolan from 10 to 20% by mass of cement, then descends. In addition, the maximum temperature of both conventional and High-strength concrete specimens significantly decreases with increasing content of natural pozzolan.

2. The relationship between compressive and flexural strength, modulus of elasticity and compressive strength of CC and HSC specimens made with different natural pozzolan content were given in formulas from (2) to (4).

3. Replacing a substantial part of Portland cement in concrete mixes will not only re-use existing industrial waste which may have negative environmental impacts but also decrease concrete products cost as well as improve properties of concrete during building high-rise buildings in the future.

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