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Application of High Content of Volcanic Ash in High Strength Concretes

[1]Sabira Zeynalova and *[1]Fikret Bayramov
[1]Norm Cement, Azerbaijan

Abstract

In this research, CEM II/A-P 42.5R cement was replaced by 20% of local volcanic ash with different Blaine values and fly ash from Turkey, and C40/50 flowing concretes were prepared. Target initial flow diameter of concretes was kept at 63±2cm. Slump-flow retention was measured after 30, 60 and 90 minutes. Complex Performance Testing System (CPTS) mortar mixer was used to determine the water demand of mortar phase of the C40/50 concretes. Hydration heat of each mortar phase was measured with the semi-adiabatic container. Heat development was observed up to 48 hours and maximum temperature, time to maximum temperature, duration of maximum temperature was compared. Finally, high content of local volcanic ash can be used in high strength flowing concrete production, and at least 11% heat reduction with VA replacement could be an advantage in mass concretes.

Key words: Volcanic Ash, Hydration Heat, High Strength Flowing Concrete

1. Introduction

High hydration heat in high strength concretes could be disadvantages. Fly ash and slag are widely used in the world as a mineral admixture in high strength flowing concretes, self-compacting concretes and mass concretes, but these additives, unfortunately, are not produced in Azerbaijan, so it is necessary to use locally available natural pozzolana like volcanic ash (VA) instead of fly ash and slag.

The researchers [1, 2] have investigated and applied the temperature-controlled casting, strength development, demoulding times and surface properties of high strength concretes in high-rise towers. They have reduced the maximum internal concrete temperature of C40 and C50 concretes below 60^0C to prevent Delayed Entergite Formation (DEF) and early age thermal cracking in deep foundations. In one project the used binders were CEM I 42.5R and slag, or CEM I 42.5R and pozzolana cement of CEM IV (B) P 32.5R [1], in another project slag cements of CEM III/A 42.5N and CEM II/B-M 42.5N [2].

The development of self-consolidating concrete using volcanic ash was investigated by the researchers [3], and they have stated that it is possible to produce SCC by using 20 to 50% VA as cement replacement. However, the replacement level of Portland cement by VA should be selected carefully in combination with water to binder ratio to achieve desired compressive strength, setting times and durability.

*Corresponding author: Address: Norm Cement, Pullman Hotel Badamdar, 5th floor, 1C M.Mushfiq str., AZ 1006, Baku AZERBAIJAN. E-mail address: fikret.bayramov@norm.az, Phone: +994772771575

In another research, volcanic ash was replaced by 0 to 25% by mass of ordinary Portland cement (OPC). Compressive strength, setting time, hydration temperature, autogenous shrinkage and porosity tests were measured. Concrete with 15% VA showed better properties compared to concrete with 10%, 20%, and 25% VA. Hydration temperature test was performed for the paste specimens with water content confirming from normal consistency test. A thermocouple was located in the center of the specimen and connected to a data logger for recording the temperature. The internal temperature of OPC specimen shows the highest as in comparison to VA specimens. The variation of internal temperature shown by each specimen indicates the different hydration process at early ages. Higher VA content shows lower hydration temperature [4].

In this research, 20% of CEM II/A-P 42.5R cement containing 7% of intergrinded volcanic ash were replaced by volcanic ash grinded up to 4028 cm^2/g and 5110 cm^2/g Blaine values and fly ash with the Blaine of 2428 cm^2/g from Turkey and used in C40/50 flowing concrete. Target initial flow diameter of concretes was 63±2cm. Slump-flow retention was measured after 30, 60 and 90 minutes. Complex Performance Testing System (CPTS) mortar mixer was used to determine the water demand of cement mortar phase of the C40/50 concretes, and also hydration heat of mortars were determined. Heat development was observed up to 48 hours and maximum temperature, time to maximum temperature, duration of maximum temperature was compared.

2. Materials and Blends Preparation

In this work, high content of VA with different Baine values were used in flowing concrete and compared with fly ash and reference cement. The aim was to replace 20% of cement with locally available volcanic ash, provide the compressive strength of C40/50 and reduce the hydration heat. Physical and chemical properties of fly and volcanic ashes are given in Table 1.

Table 1. Physical and Chemical Properties of Volcanic Ash and Fly Ash

	Unit	Fly Ash	VA with 4028 cm^2/g	VA with 5110 cm^2/g
SiO_2	%	58.77	78.02	75.51
Al_2O_3	%	21.30	4.80	5.11
Fe_2O_3	%	6.79	1.79	2.02
CaO	%	2.28	5.69	6.13
MgO	%	1.74	0.92	0.95
SO_3	%	0.28	0.20	0.55
Na_2O	%	0.84	0.97	1.00
K_2O	%	2.15	1.04	1.11
TiO_2	%	1.04	0.30	0.32
P_2O_5	%	0.34	0.07	0.07
Mn_2O_3	%	0.07	0.04	0.05
SrO	%	0.05	0.02	0.07
ZnO	%	0.02	0.00	0.01
Cr_2O_3	%	0.02	0.03	0.04
LOI	%	3.03	5.95	6.16
Fineness (residue over 40μ)	%	25.9	36.6	21.0
Density	g/cm^3	2.33	2.70	2.71
Blaine	cm^2/g	2428	4028	5110

Natural sand, crushed sand, and crushed river stone (D_{max}=16 mm) were used in flowing concrete. Sieve analyses and some physical properties of aggregates used in this work are given in Table 2.

Table 2. Physical Properties of Aggregates Used

Sieves, mm	Natural sand, %	Crushed sand,%	Crushed river stone, %
22.4	100	100	100
16	100	100	100
8	88.4	97.7	38.7
4	73.1	80.5	3.6
2	65.7	48	2.0
1	61.8	32.5	1.5
0.5	54.6	23.1	1.3
0.25	14.3	9.0	1.2
0.125	4.4	4.2	1.1
0.063	1.5	2.0	1.1
Specific Density (SSD), g/cm^3	2.63	2.65	2.66
Water absorption, %	1.7	1.0	0.8

Mineral additives were blended with the reference cement in a cement mill at the laboratory. Chemical properties of reference cement, blended cements with volcanic ashes and fly ash are given in Table 3. The cements were coded as **C, FA, VA1** and **VA2**, respectively. Here, **C:** CEM II/A-P 42.5R containing 7% VA, **FA:** CEM II/A-P 42.5R +20% fly ash, **VA1:** CEM II/A-P 42.5R +20% VA with Blaine of 4028 cm^2/g, and **VA2:** CEM II/A-P 42.5R +20% VA with Blaine of 5110 cm^2/g.

Table 3. Chemical Properties of Reference Cement, and Blended Cements with VA and Fly Ash

	C	FA	VA1	VA2
SiO_2, %	21.84	28.78	31.74	31.93
Al_2O_3, %	4.25	7.30	4.37	4.57
Fe_2O_3, %	4.48	4.87	3.95	4.05
CaO, %	59.36	48.91	49.81	50.0
MgO, %	2.02	1.94	1.78	1.79
SO_3, %	2.89	2.39	2.43	2.51
Na_2O, %	0.53	0.63	0.59	0.63
K_2O, %	0.66	0.99	0.73	0.75
TiO_2, %	0.3	0.45	0.31	0.33
P_2O_5, %	0.13	0.15	0.13	0.13
Mn_2O_3, %	0.13	0.12	0.14	0.12
SrO, %	0.33	0.28	0.32	0.28
ZnO, %	0.01	0.01	0.01	0.01
Cr_2O_3, %	0.01	0.0	0.02	0.0
LOI, %	1.13	1.43	1.69	2.38
Total,%	98.07	98.25	98.02	99.48

Table 4. Physical and Mechanical Properties of Reference Cement, and Blended Cements with VA and Fly Ash

	C	FA	VA1	VA2
Fineness (residue over 40µ), %	6.5	9.6	11.0	9.5
Specific density, g/cm^3	3.15	3.03	3.13	3.15
Blaine, cm^2/g	3831	3569	4003	4107
Water demand (EN 197-1), %	28.6	28.5	28.6	28.8
Initial setting time, min.	170	220	160	165
Final setting time, min.	250	320	230	245
2 days compressive strength, MPa	30.7	19.6	19.1	20.3
7 days compressive strength, MPa	41.5	31.0	30.6	32.8
28 days compressive strength, MPa	52.9	41.3	39.9	39.9

2nd, 7th and 28th days compressive strengths of the reference cement (C), and blended cements coded as FA, VA1 and VA2 are given in Table 4 and Figure 1. Note that 20% VA replacement reduced 13 MPa of cement strength at 28 days. Blaine of VA has not effect on cement the compressive strength at 28 days; however, 2 days and 7 days results have improved slightly.

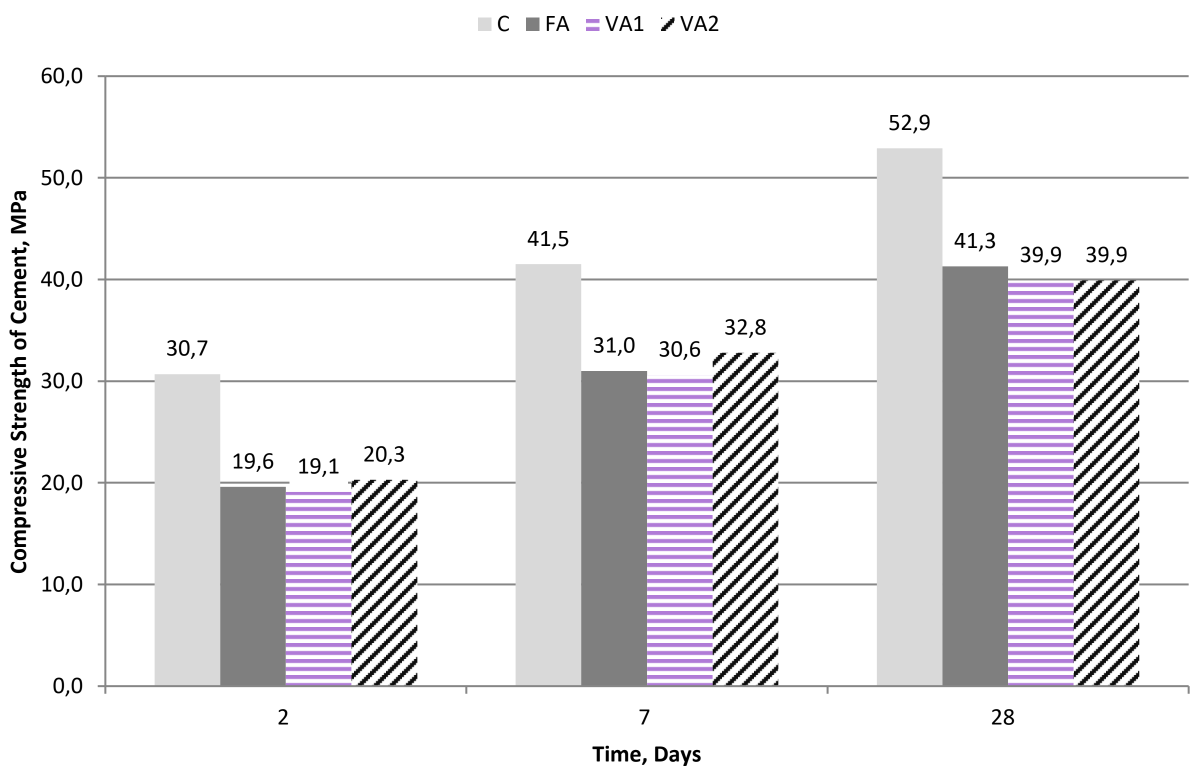

Figure 1. Compressive strength of cements

3. Concrete Mix Trials

C40/50 concrete mixtures were prepared by reference and blended cements. Natural sand, crushed sand, and crushed river stone (D_{max}=16 mm) were used as concrete aggregates in flowing concrete. Hiperplasticizer of SIKA SF18 was used as the chemical admixture. A slump-flow retention test was performed for each concrete trial. Target initial flow diameter of concretes was 63±2cm. Slump-flow retention was measured after 30, 60 and 90 minutes. Cube specimens were prepared for compressive strength tests. The concrete mix design details and the results are given in Table 5.

Table 5. Concrete Mix Design Details, Fresh and Hardened Concrete Properties

Mixture Code		**C**	**FA**	**VA1**	**VA2**
Cement content	kg/m^3	450	355	355	355
Mineral additive content	kg/m^3	0	95	95	95
Name of mineral additive		-	Fly ash	Volcanic ash	Volcanic ash
Natural sand	kg/m^3	551	546	546	546
Crushed sand	kg/m^3	416	413	413	413
Crushed river stone	kg/m^3	766	759	759	759
Water	kg/m^3	160	164	164	164
Chemical admixture		SIKA SF18	SIKA SF18	SIKA SF18	SIKA SF18
	% (kg/m^3)	1.2 (5.4)	1.2 (5.4)	1.2 (5.4)	1.2 (5.4)
Theoretical Unit Weight of Concrete	kg/m^3	2348	2337	2337	2337
Effective water/cement ratio		0.36	0.42	0.42	0.42
Fresh Concrete Properties					
Slump-flow (initial)	cm	63	64	63	62
After 30 min.	cm	62	64	59	59
After 60 min.	cm	60	64	58	58
After 90 min.	cm	58	63	58	58
Actual Unit Weight of Concrete	kg/m^3	2399	2396	2375	2379
Air Content	%	1.3	0.9	1.4	1.5
Concrete Temperature	^0C	24.1	24.1	24.1	24.0
Concrete Compressive Strength					
2 days	MPa	44.0	34.9	38.3	38.8
7 days	MPa	63.4	53.2	57.1	54.7
28 days	MPa	69.5	63.4	67.0	65.0

Slump-flow retention values of concretes are shown in Figure 2 and 2^{nd}, 7^{th} and 28^{th} days compressive strengths of C40/50 concretes are given in Figure 3.

Slump-flows of concretes after 90 minutes for the reference cement and VA blended cements are the same. So that VA replacement did not improve slump-flow retention of concretes. However, fly ash improves slump-flow retention significantly, only 1 cm flow loss occurred after 90 minutes.

20% VA and FA replacements decrease the compressive strength, slightly. The 28 days compressive strengths of cube specimens are 69.5 MPa, 63.4 MPa, 67 MP and 65 MPa for C, FA, VA1 and VA2, respectively. Nevertheless, all concretes satisfy C40/50 concrete class.

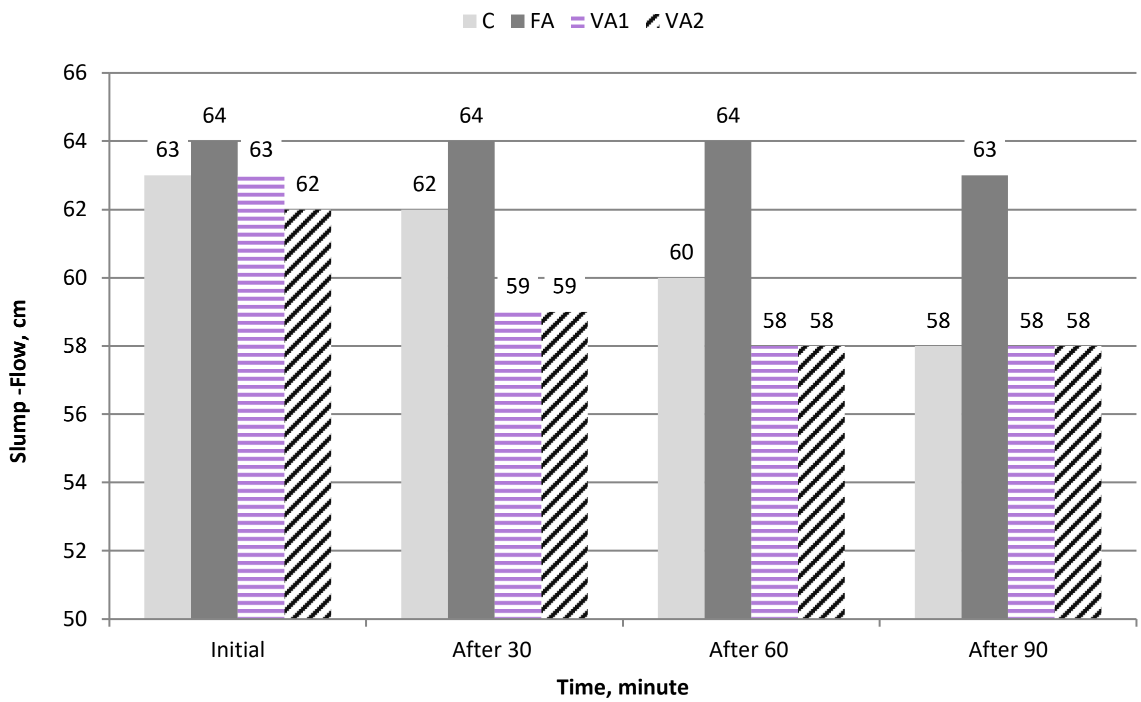

Figure 2. Slump-Flow retention values of concretes

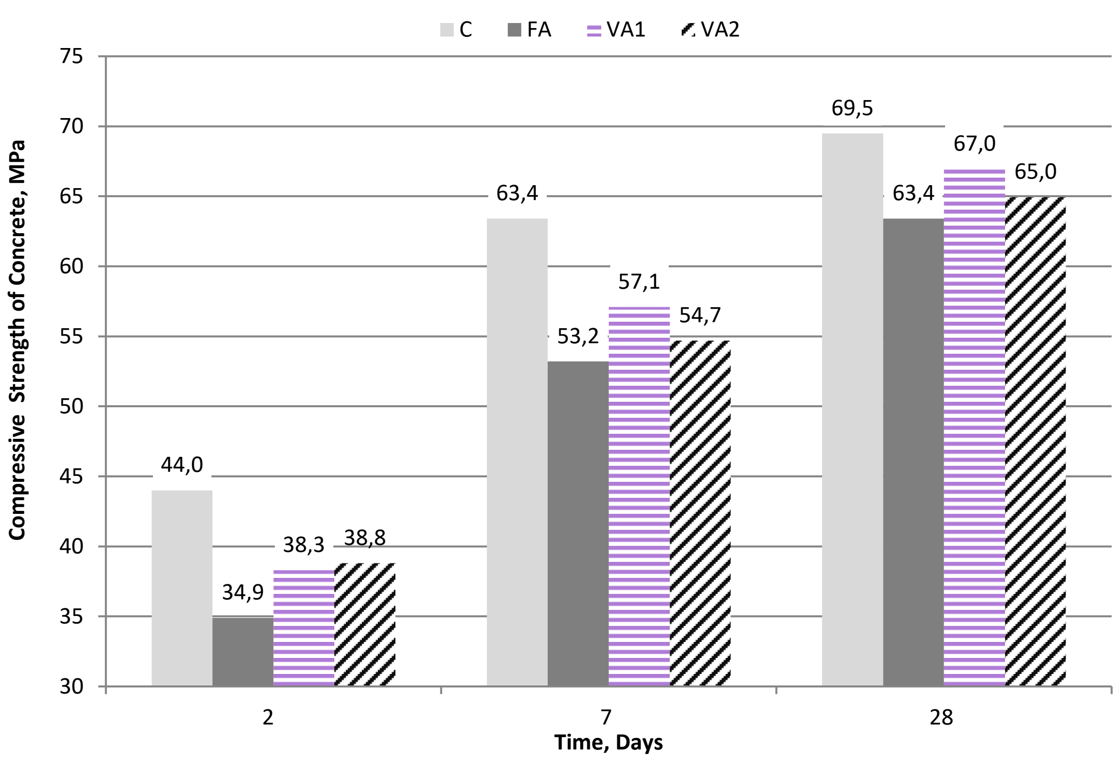

Figure 3. Compressive strength of concretes

4. Mortar Hydration Heat Tests

Hydration heat of mortars was measured in semi-adiabatic containers shown in Figure 4. Totally 12 mixes were prepared with 3 different mortar mixture types and 4 different binders. Mortar phase (under 4 mm materials) of C40/50 was calculated, and was multiplied by 1.5 to get enough amount of mortar for CPTS equipment for mixing (Figure 4).

Mortar mixture types are:
Mortar mix type 1: CEN-Standard Sand (450 g cement, 1350 g sand, and water to get 3N Torgue Value in CPTS equipment).

Mortar mix type 2: Mortar phase of C40/50 (675 g cement, 706 g natural sand sieved to 0/4mm, 493 g crushed sand sieved to 0/4mm, 5.4g chemical admixture, and water to get 1N Torgue Value in CPTS equipment).

Mortar mix type 3: Mortar phase of C40/50 (675 g cement, 706 g natural sand sieved to 0/4mm, 493 g crushed sand sieved to 0/4mm, 5.4g chemical admixture, and 271 g water (constant)).

Thermocouples were located in the center of the mortar specimen and connected to a data logger for recording the temperature. The heat of hydration was measured automatically up to 48 hours by data logger unit called Testo 176T4.

It was observed that in mortar mix type 1, VAs require approximately the same water (211 g and 214 g) as reference cement (214 g); however, fly ash requires a bit more water (220 g). This trend was the same when mortar phase of C40/50 are used. So that in mortar mix type 2, VAs require nearly the same water demand (278 g) as reference cement (280 g) does, however, fly ash requires the highest water (298 g). In mortar mix type 3, water/cement ratio of the mortar phase of C40/50 was kept constant, and 271 g water was added to all mixes (Table 6).

Figure 4. CPTS mortar equipment and hydration heat measurement test setup

Table 6. Water Demand and Hydration Heat of Reference Cement, Blended Cements with VA and Fly Ash

	C	FA	VA1	VA2
Mortar Mix Type 1	CEN-Standard Sand (NORMENSAND) with 3N constant torgue value			
Water Demand, g	214	220	211	214
Torgue Value, N	3.0	3.0	3.0	3.0
Max. Hydration Heat, ^{0}C	51.2	42.3	44.7	45.2
Time to Max, Hour, min	15 hours 43 min	14 hours 54 min	14 hours 14 min	14 hours 34 min
Duration of Max.Temperature, hr, min	12 min	1 hour 44 min	56 min	1 hour 24 min
Reduction in the heat of hydration, %		17	13	12
Mortar Mix Type 2	4mm mortar phase of C40/50 with 1N constant torgue value			
Water Demand, g	280	298	278	278
Torgue Value, N	1,0	1,0	1,0	1,0
Max. Hydration Heat, ^{0}C	66.9	54.2	55.8	56.2
Time to Max, Hour, min	17 hours 21 min	20 hours 24 min	17 hours 6 min	17 hours 57 min
Duration of Max.Temperature, hr, min	54 min	26 min	56 min	0
Reduction in the heat of hydration, %		19	17	16
Mortar Mix Type 3	4mm mortar phase of C40/50 with constant water/cement ratio			
Water Demand, g	271	271	271	271
Torgue Value, N	1.2	1.4	1.3	1.2
Max. Hydration Heat, ^{0}C	63.0	53.5	56.0	55.1
Time to Max, Hour, min	16 hours 24 min	18 hours 34 min	15 hours 47 min	16 hours 28 min
Duration of Max.Temperature, hr, min	36 min	1 hour 32 min	1 hour 12 min	40 min
Reduction in the heat of hydration, %		15	11	13

In the mortar mix type 1, maximum temperature of C, FA, VA1 and VA2 are 51.2^{0}C, 42.3^{0}C, 44.7^{0}C, and 45.2^{0}C, and the time to maximum temperature of C, FA, VA1 and VA2 are 15 hours 43 min, 14 hours 54 min, 14 hours 14 min, and 14 hours 34 min, respectively. In the mortar mix type 2, maximum temperature of C, FA, VA1 and VA2 are 66.9^{0}C, 54.2^{0}C, 55.8^{0}C and, 56.2^{0}C, and the time to maximum temperature of C, FA, VA1 and VA2 are 17 hours 21 min, 20 hours 24 min, 17 hours 6 min, and 17 hours 57 min, respectively.

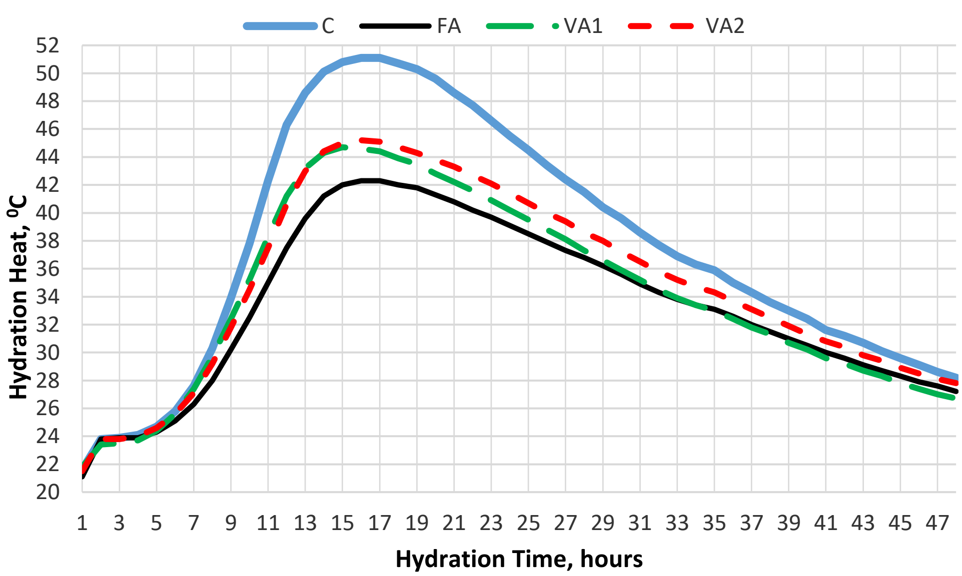

Figure 5. Hydration heat of cement mortars with CEN-standard sand (Torgue =3N)

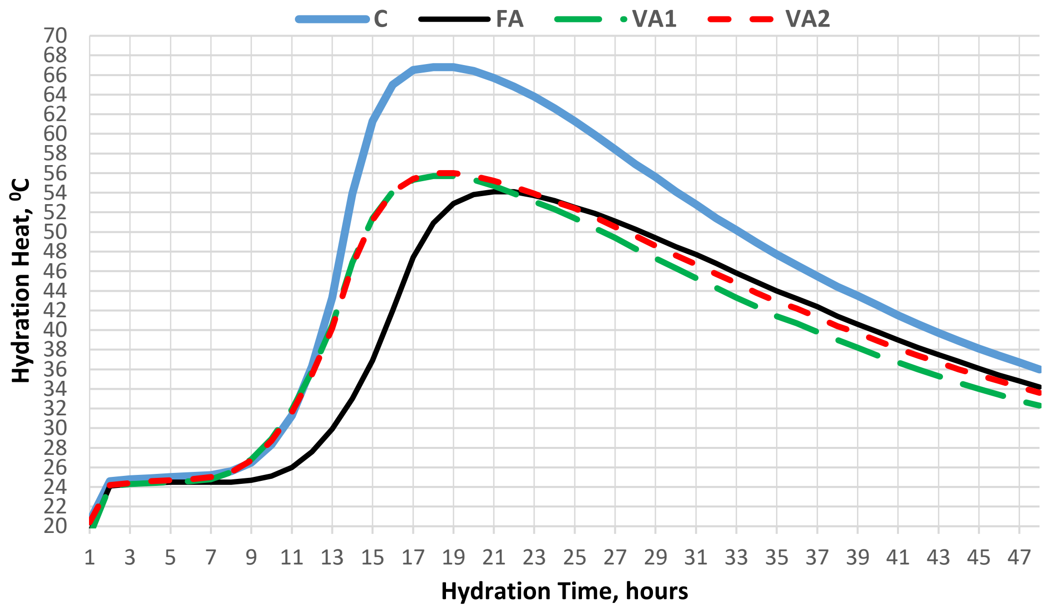

Figure 6. Hydration heat of mortar phase of C40/50 concretes (Torgue =1N)

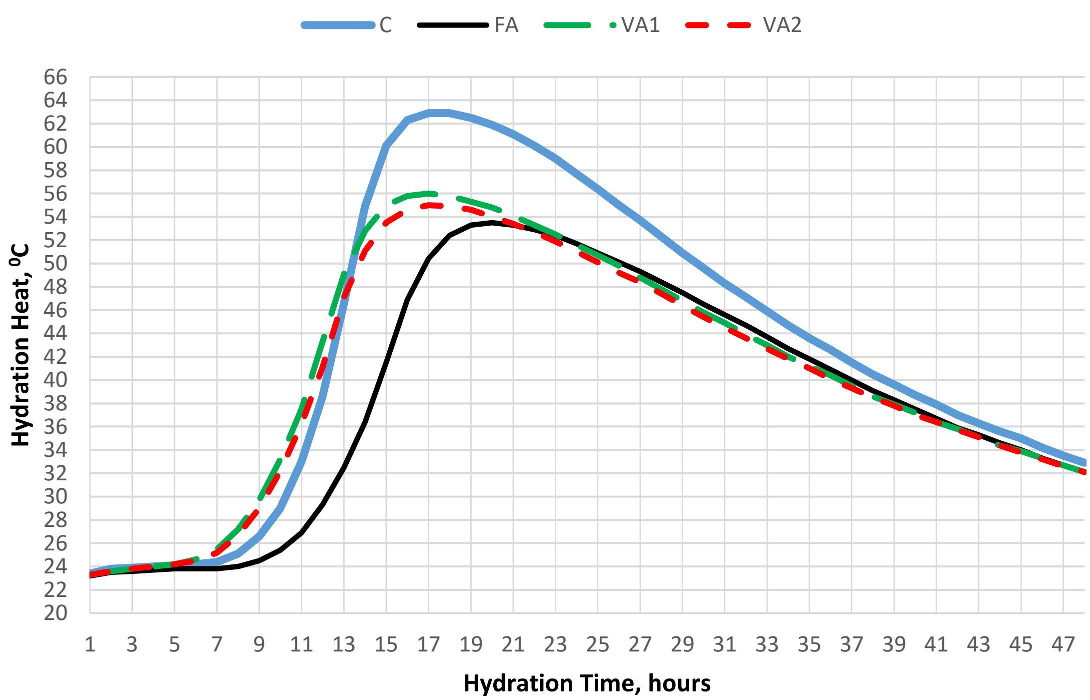

Figure 7. Hydration heat of mortar phase of C40/50 concretes (constant w/c ratio)

In the mortar mix type 3, maximum temperature of C, FA, VA1 and VA2 are 63^{0}C, 53.5^{0}C, 56^{0}C and, 55.1^{0}C, and the time to maximum temperature of C, FA, VA1 and VA2 are 16 hours 24 min, 18 hours 34 min, 15 hours 47 min, and 16 hours 28 min, respectively.

Based on the heat measurements, it can be said that the heat of hydration is reduced more than 11% when cement is replaced by 20% VA with 4028 cm^2/g. These results are in the same trend with the results of an investigation of blended cement with volcanic ash content on the hydration reaction measured by isothermal calorimeter [5]. In that research, the reduction in the heat of hydration was more than 10% when OPC replaced by 20% VA.

Consequently, 11% reduction in heat of hydration in mass concreting will reduce early age thermal cracking in concrete and help to prevent DEF.

Conclusions

Slump-flow retention test results of concretes show that VA replacement does not change slump-flow after 90 minutes. The compressive strength slightly decreases with 20% VA replacement (2-4.5MPa), however 65 and 67 MPa cube strengths satisfy C40/50 concrete class.

Fly ash improves slump-flow retention significantly, reduces the heat of hydration about 15-19%, but lowers the 28 days compressive strength (63.4MPa).

High content of locally available VA can be used in high strength flowing concrete production, and at least 11% heat reduction obtained with VA replacement could be an advantage in mass concretes.

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