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Design of Ternary Blend High-Volume Fly Ash Concrete Mixes using Hydrated Lime

C. Gunasekara, D.W. Law and S. Setunge
School of Engineering, RMIT University, Melbourne, Australia

ABSTRACT

The increase of carbon emission due to annual growth of Portland cement (PC) production has enforced research into the development of sustainable green concrete using a range of readily available industrial waste materials. The present study is focused on developing two high volume fly ash (HVFA) concretes with cement replacement levels 65% (HVFA–65) and 80% (HVFA–80). Initially, the required lime for both HVFA concrete mixes were determined, and then the optimized mix design identified, based on 28-day strength, by varying the fly ash–lime combination. The optimized mixes achieved a compressive strength of 53MPa and 40MPa, for HVFA–65 and HVFA–80 concretes, respectively. Similar to PC concrete, both HVFA concretes showed high resistance to chloride penetration, water absorption and carbonation at 28 days. The early stage strength development is dependent upon the matrix produced in the specific HVFA concrete, which is itself dependent upon the number of unreacted fly ash spheres.

Keywords: Portland cement; High-volume fly ash concrete; Compressive strength; Pozzolanic Index; Sustainability.

1.0 INTRODUCTION

Current Portland Cement (PC) production alone contributes about 5 to 7% of anthropogenic CO_2 emissions worldwide, with 0.6 to 0.8 kg of CO_2 emitted for every kilogram of cement manufactured (Gartner 2004, Meyer 2009, Chen *et al*. 2010). The damage that this level of pollution is doing to the atmosphere is unsustainable, and this has inspired research into environmentally friendly green concrete utilizing a number of the abundantly available industrial by products. The use of concrete containing high volume fly ash (HVFA) has recently gained popularity as a resource-efficient, durable and sustainable option for a variety of concrete applications. HVFA concrete is a concrete generally defined as that with at least 50% of the PC replaced with fly ash (Malhotra *et al*. 2002). However, a major drawback for HVFA concrete is low early strength development, when replacements levels exceeds 40%. On the other hand, the durability characteristics of concrete are as important as material strength since failures of concrete structures are not only caused by excessive load, but also due to the deterioration of structural components. The durability properties, such as, chloride ingress and carbonation in concrete are long term effects, with these properties potentially changing with time. Blended concretes using fly ash replacement, upto 30 %, have been shown to improve the durability properties of concrete. Hence, establishing the durability properties of HVFA concrete is a key consideration in the use and application of the material.

Shafigh *et al*. (2016) worked with HVFA concrete containing 50% fly ash, and observed compressive strength ranged between 22.1 MPa and 41.5 MPa from 7 to 90 days. Babu *et al*. (2005) showed that lightweight HVFA concrete with a density of 1725 kg/m^3 and the 28-day and 90-day compressive strengths of 12.5 MPa and 16 MPa, respectively, can be produced using 309 kg of PC and 309 Kg of fly ash in the concrete mix. Kumar *et al*. (2007) also studied HVFA concrete containing 50% fly ash and showed that compressive strength varied between 20-55 MPa at a water/cement (w/c) ratio of 0.4 and 32-80 MPa at a w/c ratio of 0.3, over a 7 to 365 days period.

The use of HVFA concrete can be beneficial where time and heat of curing is not a major factor affecting strength and concrete durability. Thus, an increase of fly ash replacement percentage in HVFA concrete while achieving comparable strength and durability to PC concrete is highly beneficial in terms of further reduction of CO_2 emission and to minimise other environmental impacts. This study is focused on developing two HVFA concrete mix designs, which contain 65% (HVFA–65) and 80% (HVFA–80) of the cement replaced with fly ash. The strength activity index was calculated using mortar compressive strength, whose results are used to determine the Pozzolanic Index, and calculate the required lime for HVFA–65 and HVFA–80 concretes.

Table 1. Chemical composition

Material	By weight (%)											aLOI
	SiO_2	Al_2O_3	Fe_2O_3	CaO	P_2O_5	TiO_2	MgO	K_2O	SO_3	MnO	Na_2O	
PC	22.5	4.5	0.4	66.3	0.67	0.20	0.51	0.15	2.8	0.10	0.17	1.7
FA	65.9	24	2.87	1.59	0.19	0.92	0.42	0.58	0	0.06	0.49	1.5

[a]Loss on ignition (unburnt carbon content)

A series of HVFA–65 and HVFA–80 concrete specimens were prepared by changing fly ash–lime combination, and the strength development examined over the period 3 to 90 days. Moreover, the resistance to chloride ingress and carbonation were investigated in order to assess the service life of this concrete.

2.0 EXPERIMENTAL PROCEDURE

2.1 Materials used

Commercially available, high early strength PC (Type 3) conforming to ASTM C150 (2016), obtained from Boral Cement Pty Ltd and low calcium class F fly ash (FA), conforming to AS 3582.1 (1998), obtained from Eraring power station in Australia, and hydrated lime conforming to AS 1672.1, obtained from Independent Cement Pty Ltd were used to manufacture HVFA-65 and HVFA-80 concretes. The chemical composition PC and FA, as determined by X-ray fluorescence analysis, is shown in Table 1. The mean particle size of FA was 20µm and fineness at 45µm sieve was 87%. Eraring FA contains 62.5% of reactive amorphous phase with non-reactive quartz (15.8%) and mullite (19.2%) as the crystalline phases, quantified by X-ray diffraction analysis. Both coarse and fine aggregate were prepared in accordance with AS 1141.5 (2000). The fine aggregate was river sand in uncrushed form with a specific gravity of 2.5 and a fineness modulus of 2.9. The coarse aggregate was crushed granite aggregate with a specific gravity of 2.6 and water absorption of 1.74%.

2.2 Mix Design

In order to calculate the quantity of lime required for the 28-day pozzolanic reaction, the Pozzolanic Index (PI), a degree of fly ash reactivity with $Ca(OH)_2$ and water in concrete, has been investigated. The mix design was prepared as specified by ASTM C 618 (2012) and ASTM C 311 (1996) with water/binder ratio of 0.484 and is shown in Table 2. Complete cement hydration is assumed at 28 days and the lime produced by hydration is assumed to be 25% (Dunstan and Zayed 2006). The equations mentioned in Table 3 (Dunstan and Zayed 2006) were used to calculate PI, and thus calculate the percentage of lime required for the HVFA-65 and HVFA-80 concrete mixes, Table 4.

The mix proportion used in each mix design is summarized in Table 5. The ratio of the components, cement, sand, coarse aggregates and mixing water, was calculated based on the absolute volume method (Neville 1996). It is noted that initially calculated HL percentage, based on PI in Table 4, is dependent on the strength activity index of [80PC+20FA] mortar mix. However, the present study is focused on concrete mix designs, and thus the HL percentage was varied from the initially calculated HL percentage, i.e. from 8–15.5 and 13–20.5 for HVFA-65 and HVFA-80 concretes, respectively.

Table 2. Mortar mix proportions (kg/m^3)

Mix Notation	PC	FA	Sand	Water	28-day Strength (MPa)
100PC	500	–	1375	242	F_c = 45.0
[80PC+20FA]	400	100	1375	242	F_{ca} = 39.9

The total binder content was fixed to 450 kg/m^3, thus the FA amount in each mix was adjusted based on HL percentage. Water/binder ratio was kept at 0.3, and the high early strength superplasticizer (Sika ViscoCrete–20HE), supplied by Sika Australia Pty Ltd in liquid form, was used together with tap water in order to maintain the workability within the range of 55–65 mm. The coarse aggregate used in concrete was in saturated surface dry condition in order to prevent the water absorption from the concrete mix.

2.3 Sample preparation and Testing

The mixing of concrete was carried out using a 120-liter concrete mixer. The dry materials (PC, FA, HL, sand and coarse aggregates) were mixed first for 4 minutes. Then water and superplasticiser were added to the dry mix and mixed continuously for another 8 minutes until the mixture was glossy and well combined. A slump test was conducted in accordance with Australian standard, AS 1012.3.1 (2014) to ensure concretes achieved the required workability. Immediately after mixing, the concrete mix was poured into moulds and vibrated using a vibration table for 2 minutes to remove air bubbles. All concrete specimens were demoulded after 1 day of casting and then cured in a water tank with saturated lime until being tested. Compressive strength testing was performed at 3, 7, 28 and 90 days using a MTS machine with a loading rate of 20 MPa/min according to AS 1012.9 (1999). Rapid chloride permeability test and water absorption test were conducted as per

ASTM C1202 and AS 1012.21, respectively, for optimized HVFA-65 and HVFA-80 concrete mixes. Accelerated carbonation testing was conducted with a 5% CO_2 concentration, 70% relative humidity and at 24 ℃. The carbonation depth was determined at 7, 14, 21 and 28 days by splitting the specimen and spraying with phenolphthalein indicator. The microstructure was observed using Scanning Electron Microscopy (SEM) imaging employing backscatter electron detector with 15 eV of energy.

Table 3. Pozzolanic Index (PI) calculations

Notation/Definition	Data	Formulae	Calculations
C_d = Density of Cement	C_d = 3150 kg/m^3	PI=B/A	PI = 0.14
C_v = Cement volume in 100PC mortar	C_v = 0.159 m^3	$B = [1.598H_{x1}C_{v1}]-[K_{Hx1}C_{v1}]-K_{Wv}$	B = -0.0122
w/c = Water/Cement of 100PC mortar	w/c = 0.484	$A = KP_w/P_d-2.85P_w/G_d$	A = -0.0877
W_v = Volume of water	W_v = 0.242 m^3	Where;	
F_c = Strength of 100PC mortar	F_c = 45.0 MPa	$K = [F_{ca}/(2.143SF)]^{1/3}$	K = 0.4721
F_{ca} = Strength of [80PC+20FA] mortar	F_{ca} = 39.9 MPa	$SF = Fc/[2.145(N/D)^3]$	SF = 177 MPa
P_w = Weight of Fly Ash	P_w = 100 kg/m^3	$N = 1.598C_vH_x$	N = 0.1716
P_d = Density of Fly Ash	P_d = 2150 kg/m^3	$D = H_xC_v+W_v$	D = 0.3494
G_d = Density of sand	G_d = 2600 kg/m^3	$H_x = (0.914\ w/c)/(w/c + 0.17)$	
w/c_1 = Water/Cement of 80PC+20FA mortar	w/c_1= 0.605	$H_{x1} = (0.914\ w/c_1)/(w/c_1 + 0.17)$	
C_{v1} = Cement volume in 80PC+20FA mortar	C_{v1} = 0.127 m^3		
H_x = Fraction of Hydrated cement	H_x = 0.676		
H_{x1} = Fraction of Hydrated cement 1	H_{x1} = 0.714		
PI = Pozzolanic Index			

Table 4. Lime requirement calculations (based on PI=0.14)

Definition	Formulae	HVFA–65	HVFA–80
Total binder	Q	450 kg/m^3	450 kg/m^3
Weight of fly ash	P_p	256.5 kg/m^3	301 kg/m^3
Weight of Cement	P_c	157.5 kg/m^3	90 kg/m^3
Hydration constant	$H_x = (0.914\ w/c)/(w/c + 0.17)$	0.763	0.821
Weight of free lime available	$0.25 \times P_c \times H_x$	30.04 kg	18.47 kg
Amount of lime reacts with fly ash	$1.85 \times PI \times P_p$	66.23 kg	77.85 kg
Weight of extra lime required	$[1.85 \times PI \times P_p] – [0.25 \times P_c \times H_x]$	36 kg	59 kg
Required extra lime percentage	$[(1.85 \times PI \times P_p) – (0.25 \times P_c \times H_x)]/Q \times 100$	8 %	13 %

Table 5. Mix designs for HVFA concrete (kg/m^3)

Mix Notation	Binder composition (%)			Mix proportions (kg/m^3)					
	PC	FA	HL	PC	FA	HL	Sand	Aggregate	Water
100PC	100	-	-	450	-	-	644	1218	135
[a]35PC+65FA	35	65	-	157.5	292.5	-	604	1144	135
[a]35PC+57FA+8HL	35	57	8	157.5	256.5	36	602	1140	135
[a]35PC+54.5FA+10.5HL	35	54.5	10.5	157.5	245.25	47.25	602	1139	135
[a]**35PC+52FA+13HL**	35	52	13	157.5	234	58.5	601	1137	135
[a]35PC+49.5FA+15.5HL	35	49.5	15.5	157.5	222.75	69.75	600	1136	135
[b]20PC+80FA	20	80	-	90	360	-	595	1126	135
[b]20PC+67FA+13HL	20	67	13	90	301.5	58.5	592	1120	135
[b]20PC+64.5FA+15.5HL	20	64.5	15.5	90	290.25	69.75	591	1119	135
[b]**20PC+62FA+18HL**	20	62	18	90	279	81	591	1118	135
[b]20PC+59.5FA+20.5HL	20	59.5	20.5	90	267.75	92.25	590	1117	135

[a]HVFA-65 concrete mixes; [b]HVFA-80 concrete mixes

3.0 RESULTS AND DISCUSSION

3.1 Compressive Strength

The results of compressive strength are reported as the average of three specimens for each mixture at 3, 7, 28 and 90 days, as shown in Fig. 1 and Fig. 2 for HVFA-65 and HVFA-80 concretes, respectively. Initially, both HVFA concrete mixes were tested for the calculated HL percentage, Table 4. Additional testing was then undertaken in 2.5% of HL increments, Table 5, in order to determine the optimum mix design. The compressive strength values were found to increase with an increase of HL percentage up to 13% and 18% for HVFA-65 and HVFA-80 concretes, respectively. At higher concentration of HL the strength started to decrease. Hence, it is noted that the [35PC+52FA+13HL] concrete mix obtained the highest compressive strength at 28 days for HVFA-65 concrete whereas the [20PC+62FA+18HL] concrete mix gave the optimum 28-day strength for HVFA-80 concrete. It was noted that addition of HL in concrete provided considerable strength evolution for both HVFA concretes between 3 and 90 days.

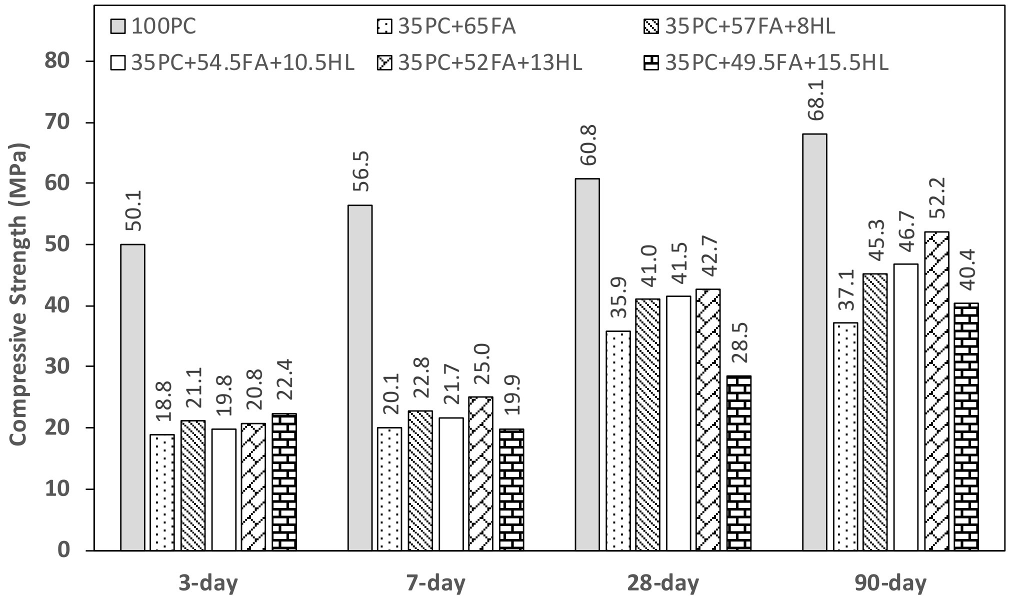

Fig. 1. The compressive strength development of HVFA–65 concrete

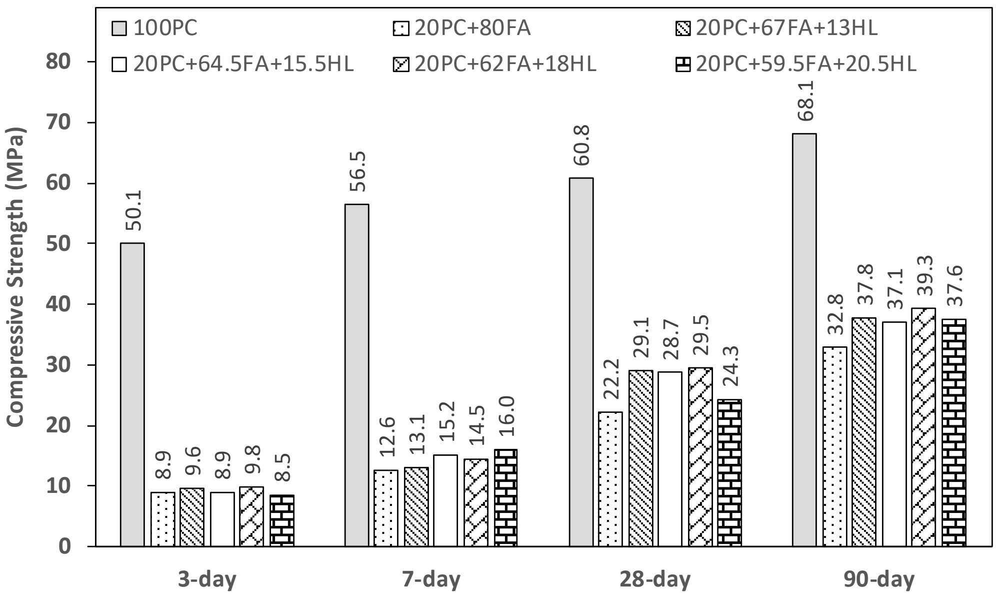

Fig. 2. The compressive strength development of HVFA–80 concrete

The optimised compressive strength of the HVFA–65 concrete increased from 20.8 to 52.2 MPa, the HVFA–80 concrete from 9.8 to 39.3 MPa and the PC concrete from 47.6 to 60.5 MPa from 3 to 90 days. Both HVFA concretes showed considerably lower compressive strength than the PC concrete after 7 days. However, the HVFA–65 concrete demonstrated a two-fold strength increase while HVFA–80 concrete had a three-fold strength gain between 3 and 28 days. However, both HVFA concretes displayed a lower compressive strength than PC concrete at all ages. The calculated strength activity index (HVFA strength/PC strength) varied between 41.6–76.5% and 19.6–57.7% for HVFA–65 and HVFA–80 concrete, respectively, Table 6. This indicated that there is on-going hydration in HVFA concretes up to 90 days, and that the percentage of strength development is significantly larger than in PC concrete over this period.

Table 6. Strength Activity Index (%)

Duration	HVFA–65	HVFA–80
3 days	41.6	19.6
7 days	44.2	25.7
28 days	70.3	46.9
90 days	76.5	57.7

3.2 Chloride Permeability

The rapid chloride permeability test (RCPT) data of PC and HVFA concretes at 28 days is displayed in Table 7.
The total charge passed (in coulombs, C) in all three concrete types are in the range of 1000–2000, thus as per ASTM C1202 standard (Shi 2003), these concretes can be classified as "low" chloride permeable concrete. The difference between the values (in coulombs) obtained for PC and HVFA–65 & HVFA–80 concretes was minimal suggesting a minor difference in their permeability. The ability of concrete to resist the penetration of chloride ions is a critical parameter in determining the service life of concrete structures exposed to deicing salts or marine environments. Hence, both HVFA concretes showed good resistance, similar to PC concrete.

In order to examine the chloride penetration depth, concrete specimens subjected to RCPT were fractured after the test. The fractured surface was then sprayed with 0.1M $AgNO_3$ solution. The chloride penetration depth (d) in Fig. 3 is indicated by the white precipitation resulting from the formation of AgCl (Otsuki *et al*. 1993). The corresponding chloride penetration depth for PC, HVFA–65 and HVFA–80 concrete is 7.9 mm, 11.7 mm and 12.4 mm respectively. This would indicate that the HVFA concretes have a lower resistance to chloride than the PC at 28 days. However, given the increase in strength with time, it would be expected that the chloride resistance would also increase, as the reaction of the HVFA continues.

3.3 Water Absorption

The water absorption test data of PC and HVFA concretes at 28 days is displayed in Table 8. In PC concrete, a water absorption less than 3% is classified as low permeable concrete, while greater than 5% is classified as high permeable concrete (Rendell *et al*. 2002). Similar to PC concrete, both HVFA-65 and HVFA-80 concretes displayed significantly lower water absorption, i.e. less than 3%, and are categorized as a low permeable concrete.

Table 7. Chloride permeability of concrete

Criteria based on ASTM C1202 (Shi 2003)		Concrete Type	Experimental data at 28 days	
Charge passed (C)	Cl^- Permeability		Charge passed (C)	Cl^- Permeability
> 4000	High	100PC	1412	Low
2000 – 4000	Moderate	HVFA-65	1502	Low
1000 – 2000	Low	HVFA-80	1556	Low
100 – 1000	Very Low			
< 100	Negligible			

Fig. 3. Chloride pentation depth in different concretes

Table 8. Water absorption of concrete

Criteria based on Rendell *et al*. (2002)		Concrete Type	Experimental data at 28 days	
Absorption (%)	Water Permeability		Absorption (%)	Water Permeability
> 5	High	100PC	2.85	Low
3 – 5	Moderate	HVFA-65	2.90	Low
< 3	Low	HVFA-80	2.95	Low

3.4 Carbonation

The measured carbonation depth of PC and HVFA concretes at 28 days are illustrated in Fig. 4. The concrete specimens were fractured after the test, and a 1% phenolphthalein ethanol solution was sprayed on the fractured surface. The depth of the colorless part from the exposure surface was measured as the carbonation depth.

The depth of carbonation measurement for HVFA–65 and HVFA–80 concretes show that the HVFA concrete experiences very low carbonation attack from carbon dioxide in the atmosphere. Carbonation depth at 28 days for both concretes is shown to be zero, as is the PC concrete.

It is hypothesized that HVFA concretes experience low carbonation, in contrast to potential high carbonation in fly ash concretes (pozzolanic concretes) due to a lower $Ca(OH)_2$ content available to react with CO_2. As such carbonation may proceed faster due to the less material available per unit area to react with CO_2. In addition, due to the large quantity of fines in HVFA concrete, which fill the pores, the porosity reduces to restrict CO_2 ingress. However, given lack of carbonation long term testing is required to establish the exact carbonation resistance of HVFA.

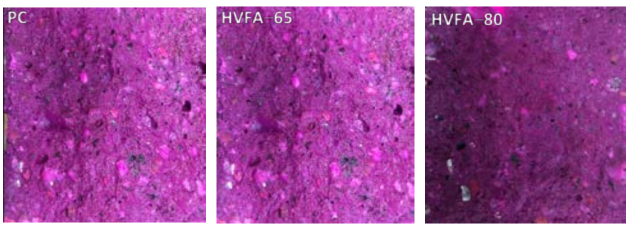

Fig. 4. Carbonation depth in different concretes

3.5 Microstructure

Figure 5 shows the microstructure observed in PC and HVFA concretes at 28 days. PC concrete has a well compacted, uniform, dense pore-structure. This is consistent with the high compressive strength, low chloride permeability and low water absorption observed in PC concrete at 28 days. Both the HVFA–65 and HVFA–80 concretes displayed a different microstructure to PC concrete, being heterogeneous in nature, with an increased number of unreacted/partially reacted fly ash spheres observed. These materials are composites, hence the strength of the unreacted fly ash particles, and the interface between them and C-S-H gel matrix is expected to have a significant bearing on the overall strength of the material (Steveson and Sagoe-Crentsil 2005). The presence of extra void spaces and microcracks were also observed from the SEM micrograph of HVFA concretes as compared to PC concrete. These observations would explain the lower strength of the two HVFA concretes at 28 days. On the other hand, the additionally generated calcium-aluminosilicate-hydrate (C-A-S-H) is expected to co-exist with C-S-H gel in the HVFA concrete, which is dependent on the degree of fly ash dissolution in alkaline $Ca(OH)_2$ solution. The addition of hydrated calcium (lime) is also expected to accelerate hardening and dissolution by providing extra nucleation sites. This may cause to the significant increase in compressive strength between 3 and 90 days in both HVFA concretes.

3.6 Long-term Durability

The long term durability of HVFA concrete is dependent upon the permeability characteristics of concrete which is associated with the ability of the surface layer to resist the penetration of water-borne chlorides and CO_2 into the HVFA concrete and initiate reinforcement corrosion. The rate of this is a function of the packing density of C-S-H/C-A-S-H gel matrix, the porosity and the connectivity of the pore structure. The data obtained suggests that HVFA–65 and HVFA–80 concretes have low chloride permeability, water absorption and carbonation at 28 days, comparable to PC performance in standard 28-day testing. However, the compressive strength data indicates that further hydration occurs in the HVFA concretes and that further long term testing is required to determine the long term performance Overall, it is believed that these characteristics and improve with age due to on-going cement-fly ash reaction, and long term durability performance is expected to be comparable to PC and blended cement concretes.

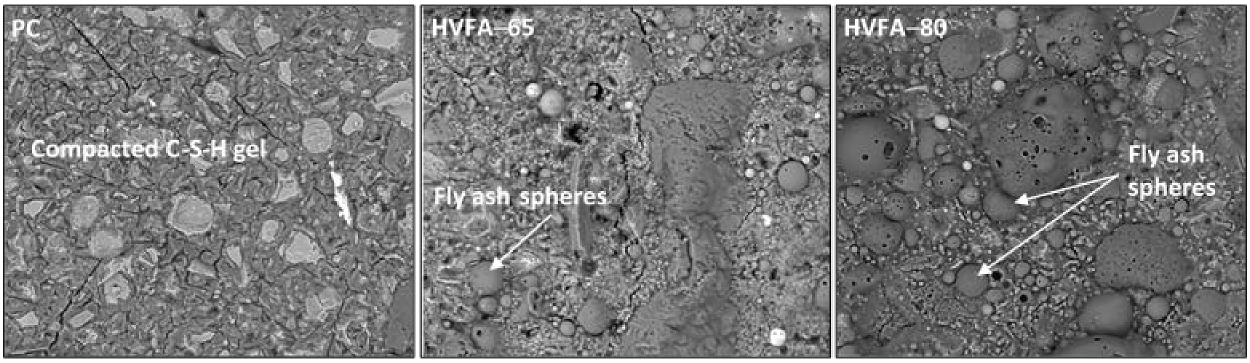

Fig. 5. Microstructure variation of PC and HVFA concretes at 28 days

4.0 SUMMARY AND CONCLUSIONS

The following conclusions can be made from the research presented in this paper:

1. Two ternary blend high-volume fly ash concrete mixes, HVFA–65 and HVFA–80, were designed using hydrated lime.
2. The compressive strength upto 53MPa and 40MPa can be achieved at 90 days, using HVFA–65 and HVFA–80 concrete, respectively.
3. The degree of fly ash dissolution and C-A-S-H gel formation governs the strength development of HVFA concrete.
4. Both HVFA concretes showed low chloride permeability, water absorption and carbonation at 28 days, comparable to PC concrete.
5. On-going cement-fly ash hydration is expected to densify the microstructure and pore-structure of HVFA concretes which in turn would be expected result in an increase in the long term durability performance.

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References

AS, 1998. Supplementary cementitious materials for use with portland and blended cement, Part 1: Fly ash. AS 3582.1

AS, 1999. Method of testing concrete, Method 9: Determination of the compressive strength of concrete specimens. AS 1012.9

AS, 2000. Methods for sampling and testing aggregates, Method 5: Particle density and water absorption of fine aggregate. AS 1141.5

AS, 2014. Determination of properties related to the consistency of concrete - Slump test. AS 1012.3.1

ASTM, 1996. Standard test methods for sampling and testing fly ash or natural pozzolans for use in portland-cement concrete. ASTM C 311

ASTM, 2012. Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for use as a Mineral Admixture in Portland Cement Concrete. ASTM C 618

ASTM, 2016. Standard Specification for Portland Cement.

Babu, D. S., Babu, K. G. and Wee, T., 2005. Properties of lightweight expanded polystyrene aggregate concretes containing fly ash. Cement and Concrete Research, 35(6): 1218-1223.

Chen, C., Habert, G., Bouzidi, Y. and Jullien, A., 2010. Environmental impact of cement production: detail of the different processes and cement plant variability evaluation. Journal of Cleaner Production, 18(5): 478-485.

Dunstan, E. and Zayed, A., 2006. A Logical Pozzolanic Index and Its Use in Concrete Proportioning. Journal of ASTM International, 3(4): 1-12.

Gartner, E., 2004. Industrially interesting approaches to low-CO2 cements. Cement and Concrete Research, 34(9): 1489-1498.

Kumar, B., Tike, G. and Nanda, P., 2007. Evaluation of properties of high-volume fly-ash concrete for pavements. Journal of Materials in Civil Engineering, 19(10): 906-911.

Malhotra, V. M., Mehta, P. K. and Development, S. C. M. f. S., 2002. High-performance, high-volume fly ash concrete: materials, mixture proportioning, properties, construction practice, and case histories, Suppementary Cementing Materials for Sustainable Development.

Meyer, C., 2009. The greening of the concrete industry. Cement and Concrete Composites, 31(8): 601-605.

Neville, A. M., 1996. Properties of Concrete. Harlow, Pearson Education Limited.

Otsuki, N., Nagataki, S. and Nakashita, K., 1993. Evaluation of the AgNO3 solution spray method for measurement of chloride penetration into hardened cementitious matrix materials. Construction and building materials, 7(4): 195-201.

Rendell, F., Jauberthie, R. and Grantham, M., 2002. Deteriorated concrete: Inspection and physicochemical analysis, Thomas Telford.

Shafigh, P., Nomeli, M. A., Alengaram, U. J., Mahmud, H. B. and Jumaat, M. Z., 2016. Engineering properties of lightweight aggregate concrete containing limestone powder and high volume fly ash. Journal of Cleaner Production, 135: 148-157.

Shi, C., 2003. Another look at the rapid chloride permeability test (ASTM C1202 or ASSHTO T277). Baltimore: FHWA Resource Center.

Steveson, M. and Sagoe-Crentsil, K., 2005. Relationships between composition, structure and strength of inorganic polymers. Journal of Materials Science, 40(16): 4247-4259.