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High volume fly ash concrete: The practical impact of using superabundant dose of high range water reducer

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ABSTRACT

The practice of using extraordinarily low water/binder ratio for high volume fly ash (HVFA) concrete mixes in order to realize adequate early strength is prevalent. Generally, superabundant dose of high range water reducer (i.e. superplasticizer) is required to make such mixes workable. The relationship between superabundant superplasticizer dose and various HVFA concrete properties is thus examined in this research work. Three groups of HVFA concrete mixes were designed for this purpose. Each group consisted of 3 mixes. Except for superplasticizer dose, the proportion of materials in the three group 1 mixes were the same, each mix containing 50% fly ash as replacement for cement. Of the three mixes, one contained maximum superplasticizer dose at 2% of binder by mass, the second contained superabundant dose at 3% while the third contained 4% dose. Group 2 and 3 mixes were similar to those of group 1 except that they contained 60% and 65% fly ash content respectively. Fresh concrete tests performed on the mixes included flow table and slump tests. Mechanical tests included compressive strength, splitting tensile strength, flexural strength and wear resistance tests. The outcome of the tests revealed that superabundant superplasticizer doses helped to obtain relatively lower water/binder ratios with good workability; led to reduction in wear/abrasion resistance; and had no observable relationship, beneficial or adverse, with the compressive, splitting tensile and flexural strengths of the HVFA concrete mixes. Increase in fly ash content was also noted to beget reduction in wear/abrasion resistance. In addition, the outcome indicated that increase in compressive strength does not necessarily translate to improved abrasion or wear resistance.

1. Introduction

The unsustainability of concrete is generally largely due to its cement content. Of all concrete constituents, cement is highly energy intensive in production and is the costliest [42]. Fly ash on the other hand is a troublesome land fill waste causing massive disposal problems especially because of its relentless mass production and severe environmental problems/hazards; it is normally produced from coal combustion during electricity production. The use of fly ash as partial replacement of cement in concrete, usually at 15–25%, is not new and has numerous advantages which mainly fall in to two categories: performance enhancement and improved sustainability [31,42]. Performance enhancements are mainly in the areas of improved relative workability, reduced bleeding, reduced heat of hydration, increased later strength among others. The improved sustainability feature is mainly in the reduction of the amount of fly ash was that goes to the landfill thereby making it a by-product. However, the impact of this reduction is considered to be minimal, or at best inadequate, because of the continual, if not continuous, production of massive tonnes of fly ash. This directly led to research into high volume fly ash (HVFA) concrete, with the hope of getting further enhanced concrete performance.

One of the key problems faced in HVFA concrete research was the very little early strength of the material [43]. Fly ash is a pozollan and hence stays inactive until the little cement in the mix reacts and develops some calcium hydroxide which then activates and reacts with the fly ash to provide extra strength for the HVFA mix. The cement is thus the only binder in the mix responsible for early strength and given its reduced availability in HVFA concrete, only a reduced early strength can be achieved. The best known solution to this problem is to reduce the water content or water/binder (cement + fly ash) ratio of HVFA concrete mixes to a minimum since reduced mixing water has long been known to improve concrete properties, including early strength [40]. However, fly ash loses its ability to improve rheological properties of concrete when used in large proportion. The only way to achieve very low water/binder is thus to use superplasticizer hence it became an essential constituent of HVFA concrete. HVFA concrete was consequently defined in terms of constituent materials proportion as

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concrete with fly ash content of 50% or above as replacement of cement by mass; with water content not beyond 130 kg/m^3 or 0.3 water/binder ratio; with cement of 200 kg/m^3 or less; and mandatory use of high range water reducer i.e. superplasticizer [35,40].

The issue with many HVFA concrete studies is that in an attempt to use a high percentage fly ash replacement of cement and keep the water/binder ratio very low below the order of 0.3 and sometimes as critically low as 0.13 (e.g. [47]) to ensure performance, a superabundant dose of superplasticizer is used so as to meet the required standard rheological properties of fresh concrete. Though the normal dose of superplasticizer ranges between 0.5% and 2.5% [44] considering that superplasticizers have similar density to water [36], numerous studies ([2,18,22,26,40,47] among others) have nonetheless used liquid superplasticizer doses ranging from 3% to over 5% of cement by mass; this represents a usage trend of twice the dose or more. High dose of superplasticizer has been said to have negative effects on setting time and mechanical properties of plain concrete [23,28]. In spite of early suggestions that superabundant superplasticizer dose may have unfavourable impact on HVFA concrete as well [41], studies have not researched such impact, especially on the set and hardened HVFA concrete properties. Instead focus has been on the effects different types of superplasticizers might have on HVFA concrete.

Accordingly, the aim of this study is to investigate the relationship between superabundant dose of superplasticizer and HVFA concrete properties. This implies that similar HVFA concrete mixes with different superplasticizer dose and different amount of water content will be compared; mixes with higher superplasticizer dose will have less water content. Class F or low calcium fly ash was used to replace cement by mass to the tune of 50%, 60% and 65% in order to prepare HVFA concrete mixes with the maximum and superabundant doses of superplasticizer employed in different mixes. The relationships between superabundant superplasticizer dose and flowability, slump, crushing strength, splitting tensile strength, flexural strength, and abrasion resistance were examined.

2. Details of experiment

2.1. Materials

The cement used to produce the mixes was Ordinary Portland Cement strength class 42.5 which conforms with CEM I 42.5N (Portland cement) of BS EN 197-1:2011 [5] standard (see Table 1). The fly ash employed was commercially available low lime fly ash conforming to [6] standard, class N (Table 1). For fine aggregate, sand with 5 mm maximum particle size conforming to [7] was used (Table 2). For coarse aggregate, graded crushed limestone with 16 mm maximum particle size conforming to [7] was used (Table 2). Specific gravity and water absorption tests were carried out on the aggregates according to BS EN 1097-6:2013 [8] standard. A commercially available Polycarboxylate light brown liquid superplasticizer which conforms to 934-2:2009+A1:2012 [9] was used. The superplasticizer has a pH value of 4.4 (±1.0), water soluble chloride content of less than 0.1% and Alkali Content of less than 0.40%. All properties stated are as given by manufacturer.

2.2. Proportion of mixes

A very important aspect of the mix proportions is the water content or water/binder ratio. Studies in the HVFA concrete area have generally approached this aspect from two main standpoints: experimental and practical or real circumstance. Morin et al. [38] for instance investigated the impact of properties of superplasticizer on concrete properties. They used constant water/binder ratio and varied only the superplasticizer dose. While this method ensured that the experimental effect of superplasticizer on the HVFA concrete mixes were established, it lacked practical reality of real circumstance since superplasticizer dose is only increased in order to decrease water content in real circumstance. In fact, in practice a set target slump is given and trial mixes are done with increasing superplasticizer doses done in tandem with decreasing water content or vice versa. This is because superplasticizer (which is also known as high range water reducer) helps concrete to achieve more workability in the absence of enough water. If all the required fresh and hardened HVFA concrete properties are achieved with a certain combination of superplasticizer dose and water content, then there is never a need to increase the superplasticizer and keep water content constant. The practical view is evident in the method of some HVFA concrete studies (e.g. [4,25,26,45]) which similarly researched the effect of superplasticizer on HVFA concrete mixes. They simply set a target slump and reduced water/binder ratio as they increased superplasticizer dose until the target slump was met for the mixes that were compared. This method gives the experiment more practical value as its results are based on what takes place in real circumstances and is the one adopted in this study.

The proportion of the materials used to produce sample mixes were determined based on Malhotra [34]. Three groups of mixes, named group one, two and three, were designed and produced. Each group consisted of three mixes. Except for superplasticizer dose, the proportion of materials in the three group one mixes were the same, each mix containing 50% fly ash as replacement for cement. Of the three mixes, one contained maximum superplasticizer dose at 2% of binder by mass, the second and third contained 1.5 times and twice the maximum dose at 3% and 4% respectively. Group two and three mixes were similar to those of group one except that they contained 60% and 65% fly ash content respectively.

With knowledge from several trial mixes, water was added to each mix until a visual inspection revealed acceptable workability corresponding to the set target slump of between 50 mm and 90 mm. Groups two and three contained the same amount of materials as group one mixes except that their fly ash content as cement replacement were 60% and 65% respectively. Their water content was determined as done for group one hence most mixes had varying water/binder ratio as would be in real circumstances. Note that extra effort was made to minimise the variation in the water/binder ratio of mixes in the same group to allow for better comparison of mixes in the same group. The given maximum superplasticizer dose was 2% of cement by mass but as in HVFA concrete experiments, this was taken to be 2% of binder (cement + fly ash) by mass. The first mix in group one was named F50. S2, with F50 indicating 50% fly ash and S2 indicating superplasticizer content of 2% of binder by mass. Also, a mix named F50. ES3 in group one will have F50 indicating 50% fly ash and ES3 indicating superabundant superplasticizer content of 3% of binder by mass. Thus a mix named F65. ES4 in group three will contain 65% fly ash and superabundant superplasticizer content of 4% (see Table 3 for full details of

Table 1
Chemical composition and Physical properties of fly ash and cement.

Physical properties	Fly ash	Cement
Fineness retained on 45 μm (%)	32	–
Specific gravity	2.75	3.15
Chemical compound (%)		
SiO_2	49.7	20.02
Al_2O_3	29.8	3.96
Fe_2O_3	7.4	3.48
CaO	3.3	65.35
MgO	1.4	1.47
K_2O	2.6	0.653
Na_2O	1.1	0.35
TiO_2	0.9	–
SO_3	0.7	2.61
Cl	0.1	0.006
LOI	3.8	< 5%

Table 2
Physical properties of aggregates.

Properties	Coarse aggregate	Fine aggregate
Maximum Aggregate size (mm)	16	5
Specific gravity	2.68	2.62
SSD Absorption (%)	0.46	0.85
Bulk density (kg/m^3)	1584	1562

mix proportions).

2.3. Preparation and casting of specimen

The mixing and production of the HVFA concrete specimens were carried out according to [10]. The mixing was done using a laboratory mixer. A target slump range of between 50 mm and 90 mm with a maximum tolerance of ±30 mm was specified for all mixes as stipulated in BS EN 12350-2:2009 [11]. This condition was used to produce numerous trial mixes. For the mixing, a water/binder ratio of 0.21 was initially used to start the process. After circa three minutes of mixing, superplasticizer mixed with water weighing the equivalent of 0.04 water/binder ratio was added to the mix, leading to a total of 0.25 water/binder ratio. With the trial mixes experience, the mix was further fed gradually with additional water until visual inspection suggested the set target slump had been met. This mixing procedure has been established to optimize the superplasticizer action on the mix [19,27,32,45].

For crushing/compressive strength test, concrete specimens of 200 mm height by 100 mm diameter were cast. For splitting tensile strength, flexural strength and abrasion/wear resistance tests, cylindrical specimen of 300 mm length by 150 mm diameter, square beams specimen of 100 mm×100 mm×350 mm length, and rectangular box specimen of 500 mm×500 mm×50 mm were cast respectively. Demoulding of specimens took place after 48 h after which the specimens were carefully arranged in a regulated curing room with temperature set at 25 °C. A total of three specimens were produced for every considered testing age.

2.4. Tests on fresh concrete

To establish the workability of the mixes, the flow table and slump rheology tests were performed. The flow table test was performed in accordance with BS EN12350-5:2009 [12] while the slump test was performed in accordance to BS EN12350-2:2009 [11]. All tests were carefully performed and outcomes carefully recorded.

2.5. Tests on hardened concrete

The cylindrical concrete specimens of 200 mm height by 100 mm diameter were tested for compressive strength in accordance with to BS EN12390-3:2000 [13] at the ages of 7, 28, 56, 91 and 365 days. The splitting tensile strength tests were carried out on the cylindrical specimens of 300 mm length by 150 mm diameter in accordance with BS EN 12390-6:2009 [15] at the ages of 7, 28, 91 and 365 days. Tests of flexural strength were carried out on the square beam specimens of 100 mm×100 mm×350 mm length according to BS EN 12390-5:2009 [14] at the ages of 7, 28, 56, 91 and 365 days. Finally, tests of abrasion resistance were carried out on the rectangular box specimen of 500 mm×500 mm×50 mm in accordance with BS EN 13892-4:2002 [16] and BS EN 13892-1:2002 [17] at the ages of 28, 91 and 365 days.

3. Results and discussion

3.1. Properties of fresh concrete

The recorded slump and flow table tests outcomes are presented in Table 4. It is clear from Table 4 that the minimum water/binder ratio that had to be used with maximum prescribed superplasticizer dose to achieve the lowly set target slump was 0.35, an increment of 16% on the upper limit of 0.3 water/binder ratio specified by Malhotra and Mehta [35]. No wonder numerous studies have had to use superabundant dose of superplasticizer in their experiments. There are however plenty of studies on the other side of the divide as well that have used prescribed superplasticizer dose to achieve low water/binder and reasonable workability (e.g. [29,30]). The existence of many studies on both sides is because workability can be dependent on various factors like properties of the constituent materials, environmental temperature of where mixing takes place, type of superplasticizer etc. Fly ash with high loss on ignition for example will require more mixing water.

It is apparent from the outcomes that group three mixes required higher water/binder ratio compared to their counterparts in group two while mixes in group two also required a higher water/binder ratio compared to group one. This indicates, in agreement with past studies (e.g. [1,2,42]), that higher fly ash content begets higher water content demand by HVFA concrete mixes. This is most pronouncing in Siddique's [42] experiment where increase in fly ash led to increase in water content and superplasticizer, and reduction in slump simultaneously. In Aydın et al.'s [2] experiment, mixes with higher fly ash percentage as binder needed more superplasticizer to achieve the same set target slump as their counterparts with lower fly ash content. In Atiş' [1] work, where mixes M5 and M7 had the same constituent material proportion, including the same superplasticizer dosage, except for difference in fly ash percentage as binder, the mix with lower fly ash content (i.e. M7) had a higher slump flow.

There are however cases where an HVFA concrete mix with the highest fly ash content offers the best workability when compared to other mixes with the same water/binder ratio and superplasticizer content as presented in some investigations (e.g. [3,24]). Results of these studies are in line with those of popular works like Malhotra [34];

Table 3
Mixture proportions.

	Group 1			Group 2			Group 3		
Mixes	F50. S2	F50. ES3	F50. ES4	F60. S2	F60. ES3	F60. ES4	F65. S2	F65. ES3	F65. ES4
Fly ash (%)	50	50	50	60	60	60	65	65	65
Cement (kg/m^3)	194	197	200	153	156	158	134	136	137
Fly ash (kg/m^3)	194	197	200	230	235	236	249	253	255
Water (kg/m^3)	136	122	112	146	129	122	146	132	125
Water/Cement ratio	0.7	0.62	0.56	0.95	0.825	0.775	1.086	0.971	0.914
Water/Binder ratio	0.35	0.31	0.28	0.38	0.33	0.31	0.38	0.34	0.32
Fine aggregate (kg/m^3)	776	788	800	766	782	788	766	778	784
Coarse aggregate (kg/m^3)	1165	1183	1199	1149	1173	1182	1149	1167	1176
SP (% of binder)	2	3	4	2	3	4	2	3	4

Binder=cement+fly ash, SP=Superplasticizer

Table 4
Slump and flow table tests results.

	Group 1			Group 2			Group 3		
Mixes	F50. S2	F50. ES3	F50. ES4	F60. S2	F60. ES3	F60. ES4	F65. S2	F65. ES3	F65. ES4
Cement (kg/m^3)	194	197	200	153	156	158	134	136	137
Fly ash (%)	194	197	200	230	235	236	249	253	255
Water (kg/m^3)	136	122	112	146	129	122	146	132	125
Water/Binder ratio	0.35	0.31	0.29	0.38	0.33	0.31	0.38	0.34	0.32
SP (% of binder)	2	3	4	2	3	4	2	3	4
Slump (mm)	100	75	65	95	80	75	85	80	70
Flow Table (mm)	650	500	440	630	540	470	560	520	470
Unit weight (Kg/m^3)	2467	2490	2508	2446	2474	2486	2444	2466	2478

SP=Superplasticizer

and Malhotra and Mehta [35]. In solving this conundrum of differences in patterns of result, it must be remembered that Mehta [37] stated clearly that the reduction of water content brought about by fly ash depends on "the quality of fly ash and the amount of cement replaced" (p. 8). So, it may be assumed that the quality of fly ash used in this study and the earlier cited works is not as high as Mehta [37] implies.

In another study by Huang et al. [29], the HVFA concrete mix with the highest fly ash content required a comparably lower water/binder ratio and had the higher slump workability when compared to other mixes with equal superplasticizer content. The incredulous mix in this case however had a relatively smaller fine aggregate content with a reduction to the tune of 60% compared to other mixes; this can at least be proposed as the theory behind the reduced water demand and increased slump.

The outcome of this study reveals that in comparison to maximum dose, superabundant dose of superplasticizer further decreases water demand of HVFA concrete mixes. This suggests that superabundant dose of superplasticizer has no adverse relationship with water demand (or workability). Comparing HVFA concrete mixes in the same group, it appears from Table 4 that the superplasticizing action per volume of superplasticizer decreases as more superabundant dose is used. It is however implausible to establish the rate of reduction in superplasticizing action from the outcome of this study, especially as the difference in water/binder ratio across mixes in a group is not symmetrical across the groups.

While considering that superabundant dose of superplasticizer further decreases water demand, it is worthy to note that liquid superplasticizers contain a certain percentage of water content. This implies that a very large dose can effectively result into a consequential increase in water/binder ratio. Poon et al. [40], for example, reported that the superplasticizer employed in their experiment contained 61.5% water content. This portends that a superabundant superplasticizer dose of 4% of binder will result in an extra 2.46 l per 100 kg of binder or an extra 0.025 water/binder ratio. This is more than the extra amount of water/binder ratio content needed (0.02) to make a 60% fly ash mix (F60. ES3) as workable as its 50% fly ash mix (F50. ES3) counterpart as evident in Table 4. Therefore, most of the modest increase in superplasticizer action realised at superabundant doses can arguably be attributed to the extra water content from the superplasticizer, as opposed to the anticipated extra chemical action.

On the whole, the set target slumps for the mixes were realised because of the wisdom from trial mixes. The minimum target was kept as low as 50 mm so as to allow the use of as small amount of water as possible for the purpose of improving mechanical properties. Results from flow table test were satisfactory as well. The proportion differences in mixes' flow table test results are similar to those of slump test results.

The unit weight of the mixes appears to decrease as the water/binder ratio increased. This is because reduction in water will cause increase in other constituent materials, which have relatively higher density, per metre cube. Like in other studies [29,30], the results tend to show that increase in fly ash content causes reduction in density (weight) when mix pairs with the same or very similar water/binder ratio like F60. S2 and F65. S2, or F60. ES3 and F65. ES3 are compared. This is logical because batching was done by weight and the fly ash used is of lower density than the cement (Table 1).

3.2. Compressive strength test results

The compressive strength test was performed on the cylindrical concrete specimens of 200 mm height by 100 mm diameter at the ages of 7, 28, 56, 91 and 365 days. The outcomes are given in Table 5 and Figs. 1 and 2. The compressive strength of all the mixes increased with age as expected.

Each chart in Fig. 1 compares the compressive strength of mixes in the same group. From the mix proportions, the more the superplasticizer, the lesser the water/binder ratio. The relationship between water content (or water/binder ratio) and compressive strength is apparent as mixes with the least water content (F50. ES4, F60. ES4 and F65. ES4) and the ones with the most water content (F50. S2, F60. S2

Table 5
Compressive strength results.

	Mixes	Water/binder ratio	SP (% of binder)	7 days	28 days	56 days	91 days	365 days
Group 1	F50. S2	0.35	2	16.5	28.0	31.8	33.2	35.6
	F50. ES3	0.31	3	21.6	32.6	38.4	44.9	52.9
	F50. ES4	0.28	4	24.7	37.8	42.5	51.2	60.9
Group 2	F60. S2	0.38	2	15.7	25.2	30.1	32.4	37.2
	F60. ES3	0.33	3	19.2	31.1	36.1	44.2	55.5
	F60. ES4	0.31	4	22.2	34.2	40.2	50.7	62.8
Group 3	F65. S2	0.38	2	15.1	24.9	29.3	31.8	37.9
	F65. ES3	0.34	3	18.5	30.7	35.2	43.8	56.7
	F65. ES4	0.32	4	21.6	32.1	39.4	50.3	63.1

SP =Superplasticizer

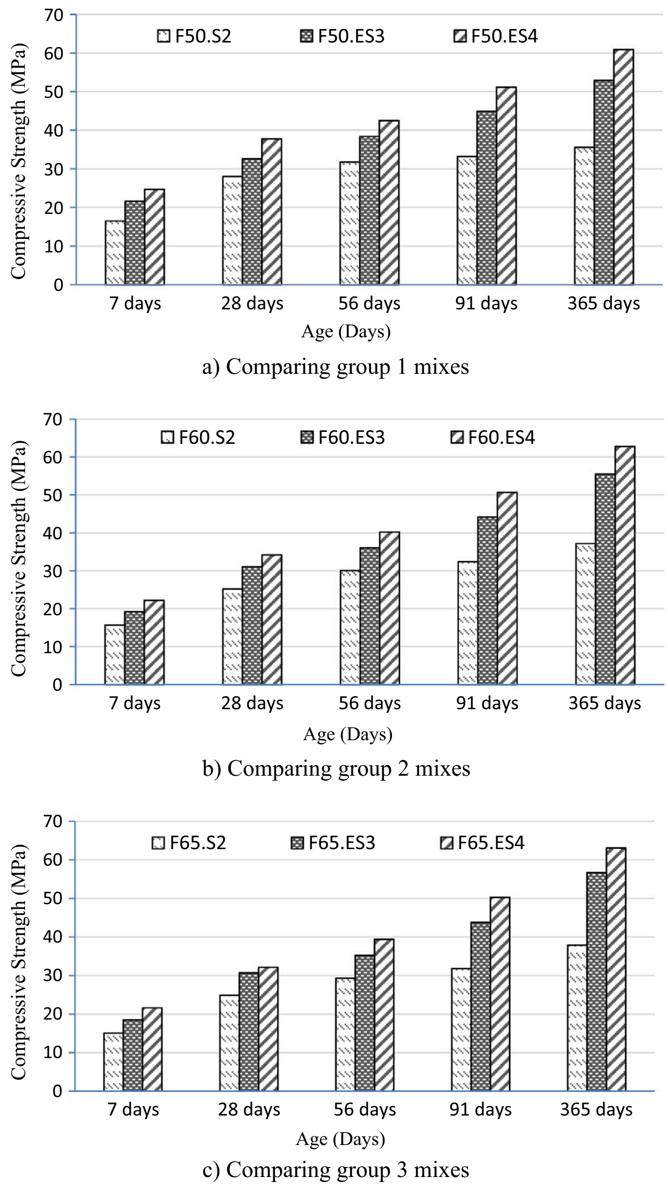


Fig. 1. Charts comparing compressive strength versus age of mixes in the same group.

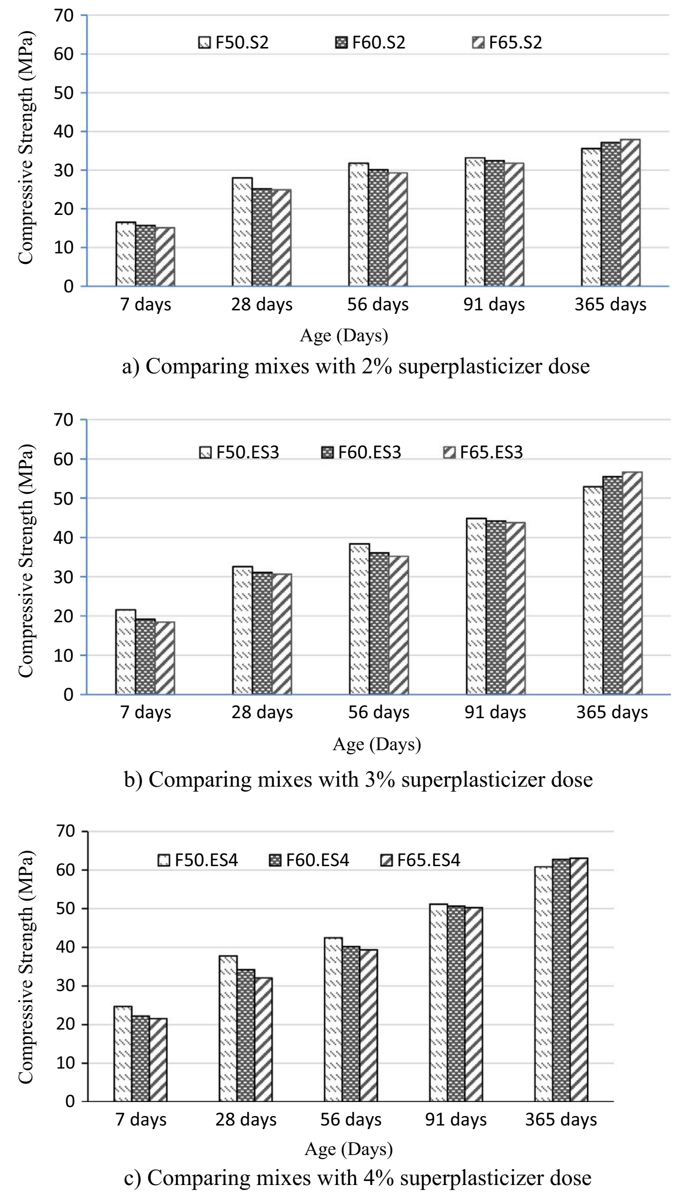


Fig. 2. Charts comparing compressive strength versus age of similar mixes with different proportion of fly ash content.

and F65. S2) have the highest and lowest compressive strengths respectively at all ages. As generally known and confirmed in past studies (e.g. [3,24,33–35,37,40] to mention a few), the results show that reduction in mixing water (corresponding to increase in superplasticizer dose) increases early and overall compressive strength of HVFA concrete (Fig. 1). This, according to the mix proportions, implies that an increase in superplasticizer content begets an increase in compressive strength. This hypothesis about superplasticizer is however not technically right since water reducing superplasticizer does not improve strength. The key point here is that the superplasticizer dose does not seem to have any directly observable beneficial or adverse relationship with the compressive strength of the HVFA concrete mixes. Rather it is the reduced mixing water that the superplasticizer has helped to achieve that is responsible for the increase in strength. Overall, it appears non-detrimental to use superabundant dose of superplasticizer, as much as twice the prescribed dose, to achieve very low water/binder ratios for HVFA concrete mixes as far as compressive strength is concerned. The results also indicate that to achieve mixes with good early strength and better overall strength, it is imperative to use as small as possible water/binder ratio. This supports the motion that HVFA concrete mixes can be used for structural concrete.

Each chart in Fig. 2 compares the compressive strength of mixes that have the same superplasticizer content but different proportion of fly ash content across the groups. Most of the mixes gained only between 50% and 70% of their one-year strength at 28 days. It can be deduced from the charts (Fig. 2) that increase in fly ash content causes relatively reduced early strength. This is because only the cement content goes through the hydration reaction at the early stage while the fly ash remains inactive. Virtually all the early strength could be attributed to only the cement content in the mix. While mixes with lower fly ash content had higher strength at early ages, mixes with higher fly ash content developed better strength between 91 and 365 days, implying more hydration reaction at later ages for mixes with higher fly ash content.

3.3. Flexural strength test results

Flexural strength is a fundamental and important property of pavement concrete and horizontal structural concrete elements like beams and slabs, which are typically subjected to bending. Flexural strength tests of the square beams specimen of

100 mm×100 mm×350 mm length were carried out at the ages of 7, 28, 52, 91 and 365 days. The outcomes are given in Table 6 and in the charts presented in Figs. 3 and 4. Each chart in Fig. 3 compares the flexural strength of mixes in the same group (group one, two or three). The flexural strength of all the mixes increased with age as expected.

The mixes gained observable strength at the ages of 56, 91 and 365 days due to the presence of fly ash in them. Also, like in the case of compressive strength, decrease in water/binder ratio (corresponding to increase in superplasticizer dose) appear to lead to increase in flexural strength across HVFA concrete mixes. This claim is made as mixes with the lowest water/binder ratio, corresponding to highest superplasticizer content (i.e. F50. ES4, F60. ES4 and F65. ES4), gained the most flexural strength (Fig. 3).

Just as with compressive strength test outcomes, superabundant dosage of superplasticizer cannot be said to have any adverse relationship with the flexural strength of the HVFA concrete mixes, at least not from the outcomes of this study.

However, unlike in the case of compressive strength, increase in fly ash seem to cause reduction in overall flexural strength when mixes with the same superplasticizer content but different fly ash content are compared (Fig. 4). The most fitting pair of mixes to this claim are F60. S2 and F65. S2 as they both contain exactly the same materials proportion (including water/binder ratio) except fly ash content, yet F65. S2 which contained more fly ash gained a relatively overall lower strength. Considering the scale of the vertical axis (i.e. flexural strength) in the charts (Fig. 4), it can be concluded that the reduction in flexural strength caused by increase in fly ash is slight. On the whole, only F50. ES4 and F60. ES4 achieved the minimum 4.0 MPa 28-d flexural strength requirement of the British Airport Authority for pavement construction concrete [20].

3.4. Splitting tensile strength test results

The splitting tensile strength tests were performed on the cylindrical specimen of 300 mm length by 150 mm diameter at the ages of 7, 28, 91 and 365 days. The outcomes are given in Table 7 and in the charts presented in Figs. 5 and 6. Each chart in Fig. 5 compares the splitting tensile strength of mixes in the same group (group one, two or three).

The results trend is understandably very much like that of flexural strength test as both are used to assess the tensile strength property of concrete. All mixes had an increment in splitting tensile strength as they aged. With the arguable exception of F50. S2 and F60. ES4 (Table 7), no mix had significant increase in splitting tensile strength between 91 and 365 days despite the much expected extra hydration during that period. A reduction in water/binder ratio (corresponding to increase in superplasticizer dosage) generally led to increase in splitting tensile strength (Fig. 5) while increase in fly ash content led to overall decrease in splitting tensile strength (Fig. 6), just as for flexural strength. From the results, the superplasticizer dose cannot be concluded to have any definitive relationship with the splitting tensile strength of the HVFA concrete mixes.

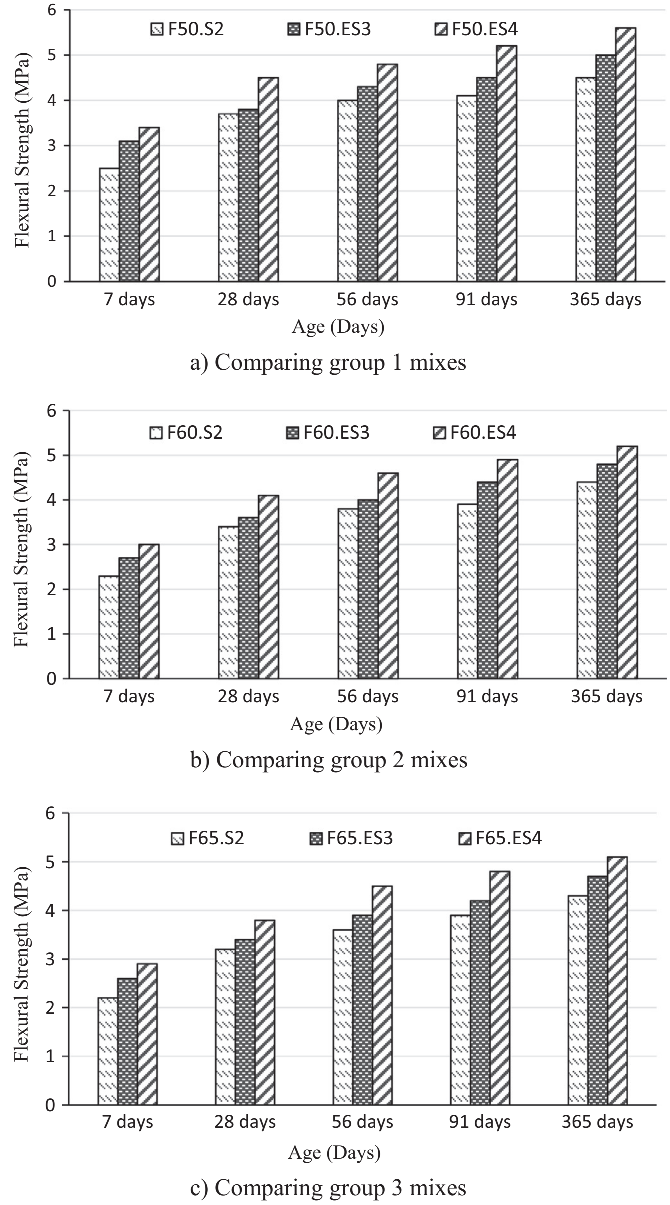


Fig. 3. Charts comparing flexural strength versus age of mixes in the same group.

As evident from the results in Table 7, except for F60. S2 and F65. S2, all other mixes achieved the minimum required 7-d splitting tensile

Table 6
Flexural strength results.

	Mixes	W/b ratio	SP (% of binder)	7 days	28 days	56 days	91 days	365 days
Group 1	F50. S2	0.35	2	2.5	3.7	4.0	4.1	4.5
	F50. ES3	0.31	3	3.1	3.8	4.3	4.5	5.0
	F50. ES4	0.28	4	3.4	4.5	4.8	5.2	5.6
Group 2	F60. S2	0.38	2	2.3	3.4	3.8	3.9	4.4
	F60. ES3	0.33	3	2.7	3.6	4.0	4.4	4.8
	F60. ES4	0.31	4	3.0	4.1	4.6	4.9	5.2
Group 3	F65. S2	0.38	2	2.2	3.2	3.6	3.9	4.3
	F65. ES3	0.34	3	2.6	3.4	3.9	4.2	4.7
	F65. ES4	0.32	4	2.9	3.8	4.5	4.8	5.1

W/b ratio = water/binder ratio, SP = Superplasticizer

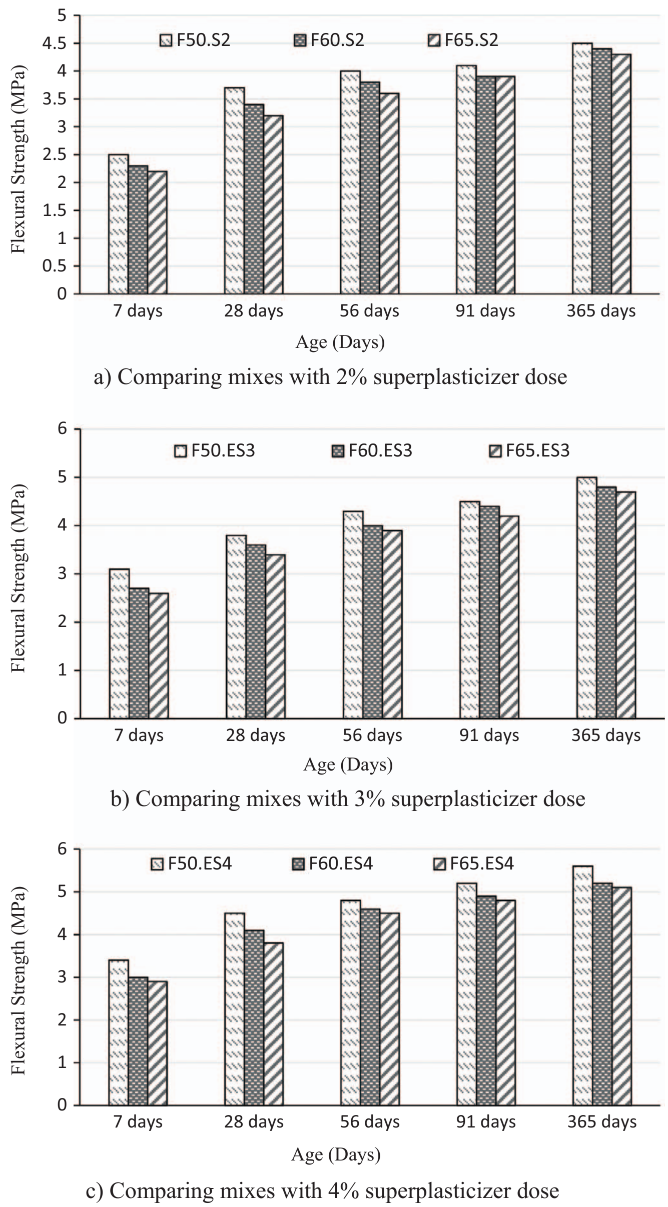


Fig. 4. Charts comparing flexural strength versus age of similar mixes with different proportion of fly ash content.

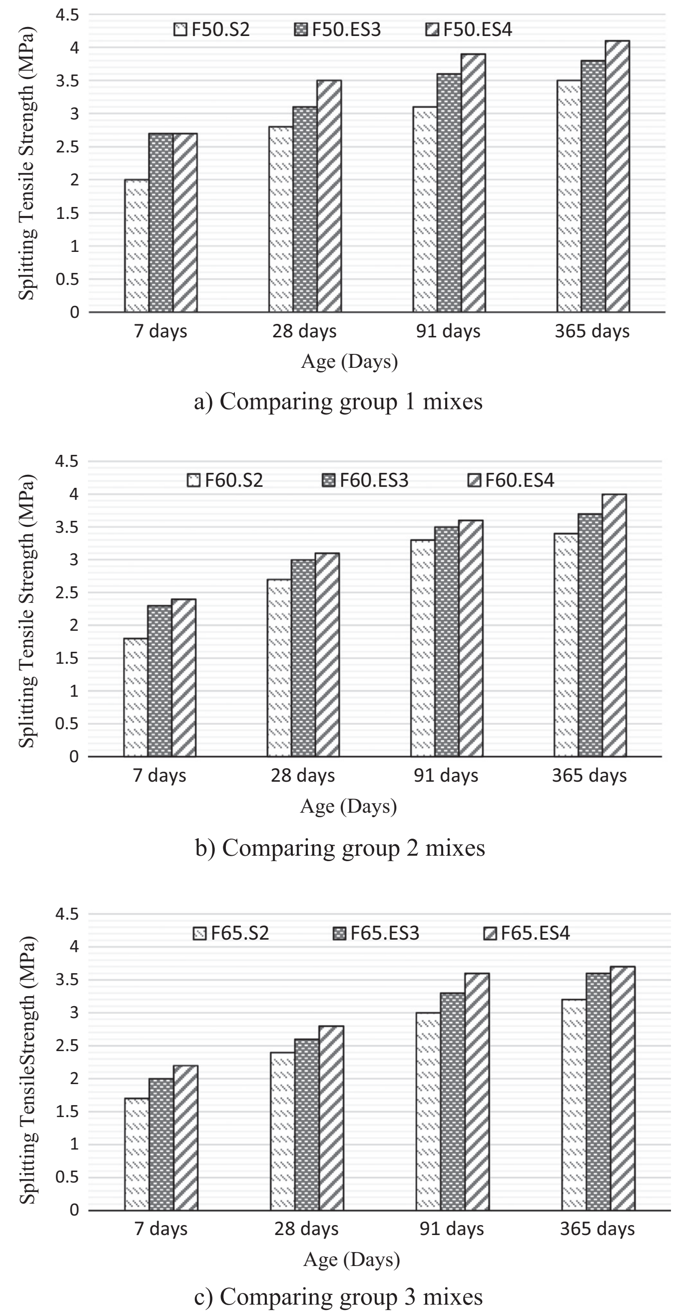


Fig. 5. Charts comparing splitting tensile strength versus age of mixes in the same group.

Table 7
Splitting tensile strength results.

	Mixes	W/b ratio	SP (% of binder)	7 days	28 days	91 days	365 days
Group 1	F50. S2	0.35	2	2.0	2.8	3.1	3.5
	F50. ES3	0.31	3	2.7	3.1	3.6	3.8
	F50. ES4	0.28	4	2.7	3.5	3.9	4.1
Group 2	F60. S2	0.38	2	1.8	2.7	3.3	3.4
	F60. ES3	0.33	3	2.3	3.0	3.5	3.7
	F60. ES4	0.31	4	2.4	3.1	3.6	4.0
Group 3	F65. S2	0.38	2	1.7	2.4	3.0	3.2
	F65. ES3	0.34	3	2.0	2.6	3.3	3.6
	F65. ES4	0.32	4	2.2	2.8	3.6	3.7

W/b ratio = water/binder ratio, SP = Superplasticizer

strength of 1.85 MPa specified for road construction concrete by the British Department of Transport [21].

3.5. Abrasion resistance test results

The tests of resistance to abrasion were performed on the rectangular box specimens of 500 mm×500 mm×50 mm at the ages of 28, 91 and 365 days; the results are given in Table 8 and Figs. 7 and 8. For each specimen, the abrasion resistance testing device was operated for circa 15 min to apply 2850 (± 5) revolutions. Just as with other properties, the abrasion severity or wear depth of all mixes reduced (i.e. abrasion resistance increased) with age.

The charts in Fig. 7 compare the abrasion severity or wear depth in micro metres (μm) of mixes in the same group (group one, two or three). As opposed to other properties, the wear depth increased (i.e.

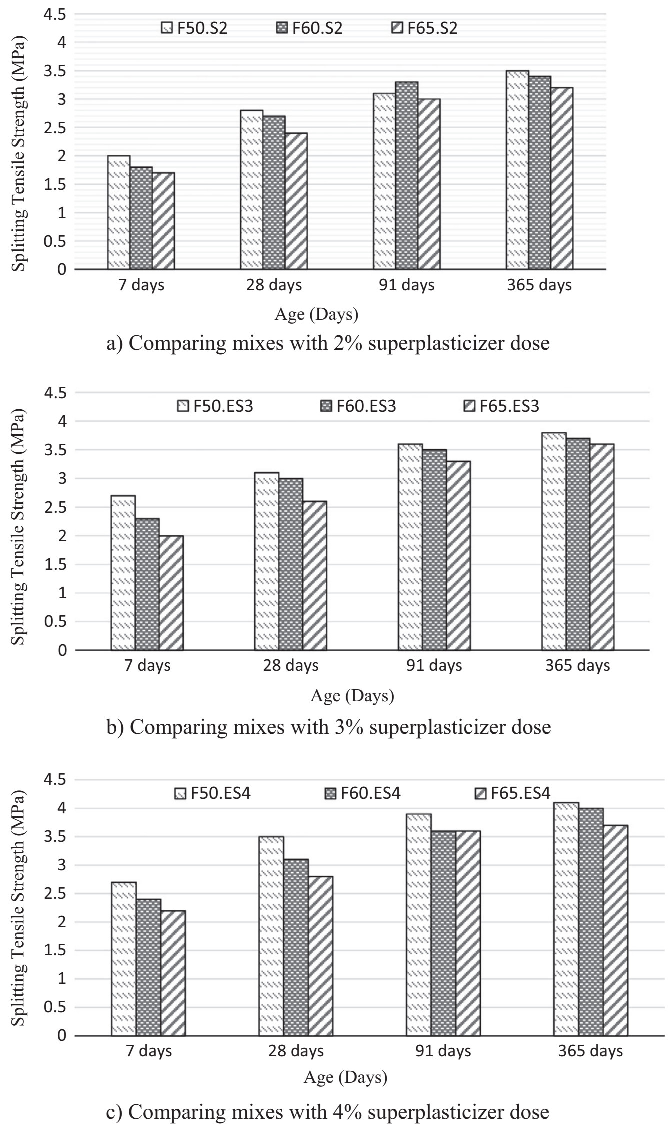


Fig. 6. Charts comparing splitting tensile strength versus age of similar mixes with different proportion of fly ash content.

Table 8
Abrasion resistance results.

	Mixes	W/b ratio	SP (% of binder)	28 days	91 days	365 days
Group 1	F50. S2	0.35	2	250	220	190
	F50. ES3	0.31	3	280	250	220
	F50. ES4	0.28	4	280	260	230
Group 2	F60. S2	0.38	2	290	250	220
	F60. ES3	0.33	3	300	260	240
	F60. ES4	0.31	4	310	280	250
Group 3	F65. S2	0.38	2	310	270	250
	F65. ES3	0.34	3	320	290	260
	F65. ES4	0.32	4	340	300	260

W/b ratio = water/binder ratio, SP = Superplasticizer

abrasion resistance reduced) with increase in superplasticizer despite the fact that mixes with higher superplasticizer content have lower water/binder ratio which helps improve mechanical properties of concrete. This clearly depicts that superabundant superplasticizer dose has an adverse relationship with the abrasion resistance property of

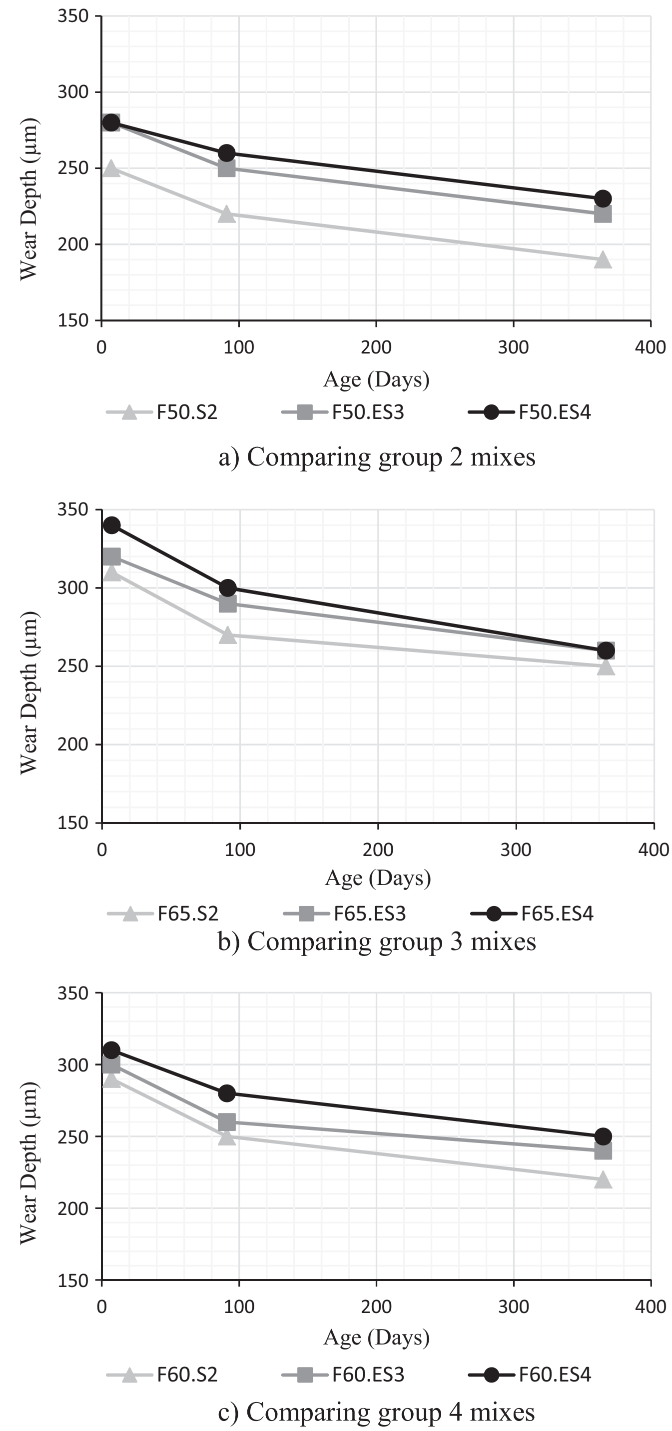
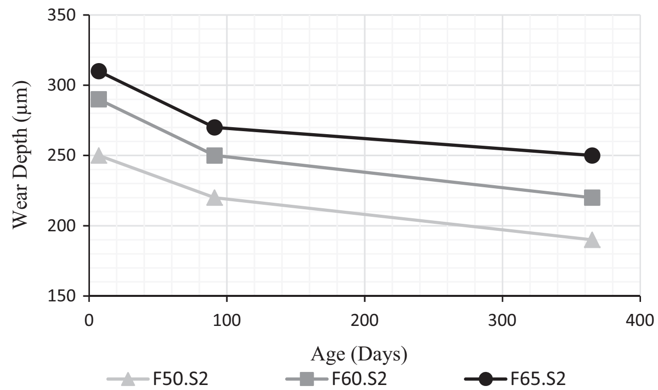


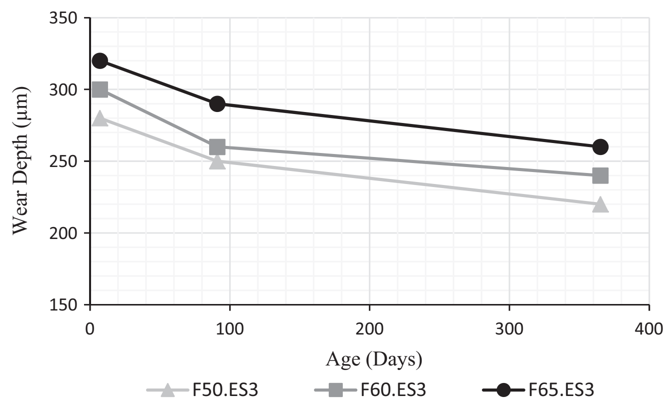
Fig. 7. Charts comparing wear depth versus age of mixes in the group.

HVFA concrete. The adversity however reduces with increase in fly ash content (Fig. 7).

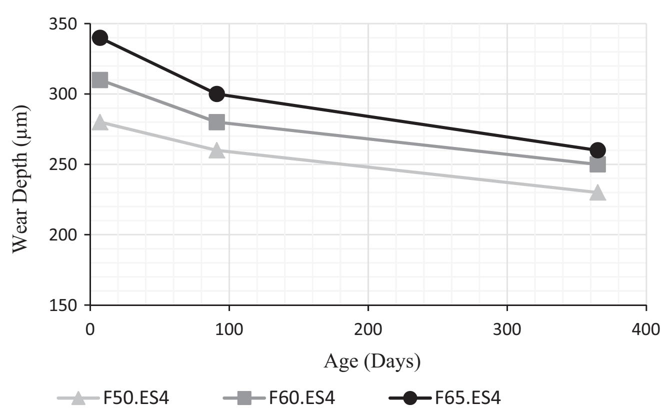
Fig. 7 also shows a trend of increasing rate of wear at later ages (between 91 and 365 days) compared to the early ages (between 28 and 91 days) for all the mixes. However, it will be illogical to conclude that this was caused by superabundant superplasticizer dose. On the whole, it is evident that superabundant superplasticizer dose is harmful to HVFA concrete mixes to be used in applications like concrete pavement, concrete railway sleepers, warehouse floors etc. where abrasion resistance is very essential. For such applications, rapid hardening cement can be used to achieve early strength in HVFA concrete mixes [35] as against superabundant use of superplasticizer to achieve very



a) Comparing mixes with 2% superplasticizer dose



b) Comparing mixes with 3% superplasticizer dose



c) Comparing mixes with 4% superplasticizer dose

Fig. 8. Charts comparing wear depth versus age of similar mixes with different proportion of fly ash content.

low water/binder ratio.

The charts in Fig. 8 compare the abrasion severity or wear depth in micro metres (µm) of similar mixes with different proportion of fly ash content. The charts indicate that increment in fly ash causes increased wear depth (or reduced abrasion resistance), with a more pronounced effect than that from too much superplasticizer, as demonstrated in some other studies as well (e.g. [39,46]). This implies that increase in compressive strength does not necessarily translate to improved abrasion or wear resistance. As noted before, the results show a trend of increasing rate of wear at later ages (between 91 and 365 days) compared to the early ages (between 28 and 91 days) for all the mixes. This suggests that the late hydration of HVFA concrete mixes cannot be concluded to boost their abrasion resistance. A possible mechanism for this scenario is that the extra hydration product produced by late hydration of fly ash mainly fills the internal pores, as against surface pores, thereby increasing the compressive strength of the HVFA concrete. Abrasion resistance on the hand has to do mainly with bond of surface particles' resistance to continual or continuous surface friction/rubbing hence late hydration of fly ash might not contribute to this resistance.

4. Conclusion

The conclusions that can be drawn from this study are as follows:

1) Superabundant superplasticizer dose has an adverse relationship with the wear resistance property of HVFA concrete. It can also be concluded that increase in fly ash begets reduction in wear resistance.
2) HVFA concrete with superabundant superplasticizer dose is not the best for applications like concrete pavement, concrete railway sleepers, warehouse floors etc. where abrasion resistance is highly essential
3) Superabundant superplasticizer dose, compared to prescribed dose, can help to achieve exceptionally low water/binder ratios with good fresh concrete properties in terms of flow and slump for HVFA concrete.
4) When superabundant superplasticizer dose is used, it appears the superplasticizing action per volume decreases as more dose is added.
5) Superabundant superplasticizer dose has no observable relationship, beneficial or adverse, with the compressive strength, flexural strength and splitting tensile strength of HVFA concrete.
6) If superabundant superplasticizer dose is used to achieve very low water/binder ratio for HVFA concrete mixes, the mixes can achieve good early and long term compressive strength.
7) High compressive strength does not necessarily translate to good abrasion resistance for HVFA concrete.
8) If superabundant superplasticizer dose is used to achieve very low water/binder ratio for HVFA concrete mixes, the mixes can meet the minimum 28-d flexural strength and 7-d splitting tensile strength of various standards.
9) The higher the fly ash content in HVFA concrete mixes, the higher the overall compressive strength becomes and the lower the overall flexural strength, splitting tensile strength and abrasion resistance become.

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