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Effect of Excess Dosage of Superplasticizer on the Properties of the highly Sustainable High Volume Fly Ash Concrete
Abstract

It is quite common for researchers to use excess dosage of superplasticizer to achieve the desired very low water/binder ratio required for sustainable high volume fly ash (HVFA) concrete mixes in order to obtain early strength without reporting on the effects of the excess dosage. This study investigated the effects of such excess dosage on the highly sustainable HVFA concrete properties. Four series of concrete mixes were designed. Series 0 being the control concrete mix containing no fly ash and no superplasticizer. Series 50, 60 and 65 contained HVFA concrete mixes that had 50%, 60% and 65% fly ash content respectively. Each of series 50, 60 and 65 contained three similar mixes. In each series, the three mixes were prepared with maximum dosage of superplasticizer at 2% of binder by mass, and excess dosages at 3% and 4% respectively. The effect of the excess doses on slump, flowability, compressive strength, flexural strength, tensile splitting strength, and abrasion resistance were investigated. Results showed that excess dosage of superplasticizer helped to achieve increased workability, caused a decrease in abrasion resistance and had no decisive effect, good or bad, on the compressive, flexural and tensile splitting strengths of HVFA concrete mixes. Increase in fly ash content in HVFA concrete mixes resulted in reduced overall flexural strength, tensile splitting strength and abrasion resistance. Not using a very low w/b ratio, which can be achieved by using excess dose of superplasticizer, will make HVFA concrete mixes struggle to meet the minimum required compressive, flexural and tensile splitting strengths of various standards. It is concluded that although HVFA concrete, which is normally prepared with high dosage of superplasticizer, is highly sustainable, it is not the best for applications like industrial floors where wear/abrasion resistance is of vital importance.

Keywords

Concrete; Fly ash; Superplasticizer dosage; Compressive strength; Abrasion resistance; Sustainability; Flexural strength; tensile splitting strength.

1.0 Introduction

One of the unsustainable features of concrete is the cement production process which is responsible for approximately 5% of the global anthropogenic CO₂ emissions (Humphreys and Mahasenan, 2002) hence the efforts to reduce cement content in concrete. The
concrete properties enhancement, including its sustainability, brought about by the partial
replacement of cement with fly ash is well known and documented in the civil engineering
materials world. Fly ash concrete’s contribution to the reduction in fly ash as land fill waste
and the cutback on consumption of cement, whose production process is energy intensive
and causes depletion of natural resources, makes it a sustainable material on multiple fronts.
The unprecedented and unsustainable colossal amount of fly ash generated by coal plants
however initiated calls for substantial increase in use of fly ash in cement related products.
The consequence of this was the emergence of various studies on using large proportion of
fly ash to replace cement in concrete to produce a highly sustainable concrete (Giaccio and
Malhotra, 1988; McDonald, 1994; Atis, 2003; Sukumar, et al., 2008; Şahmaran and Li, 2009;
Papayianni and Anastasiou, 2010; and more); a study area, or material, now popularly
known as high volume fly ash (HVFA) concrete.

Following pioneering studies on the highly sustainable HVFA concrete by Malhotra and
others (Malhotra, 1989; Malhotra and Painter, 1989; Langley et al., 1989; Alasali and
Malhotra, 1991), and subsequent studies in the area, HVFA concrete was defined in terms of
proportion of constituent materials. It was defined as concrete with not less than 50% fly ash
replacement of cement by mass; with water content of not more than 130 kg/m³ or 0.3
water:binder (i.e. cement and fly ash) ratio; with cement content of not more than 200 kg/m³;
and the compulsory use of a high-range water-reducing admixture (superplasticizer) among
other requirements (Malhotra and Mehta, 2002). Malhotra and Mehta (2002) however also
noted that anything from 30% fly ash replacement in concrete can be considered as high.
The furtherance in HVFA concrete research was going to help reduce the unsustainable
dumping of fly ash.

Although fly ash, when used in moderate proportion (i.e. 15% to 20%) as cement
replacement, improves rheological properties of concrete (Malhotra and Mehta 2002), HVFA
concrete needs superplasticizer for two reasons: (i) fly ash loses its ability to improve
rheological properties of concrete when used in large proportions (ii) fly ash slows down the
hydration reaction of concrete hence HVFA concrete has a very low rate of early strength
gain and thus needs as little as possible mixing water to mitigate this effect. This means
superplasticizer plays a key role in producing the highly sustainable HVFA mixes if they are
to be practically useful. Majority of studies involving large proportion of fly ash in concrete
have consequently employed superplasticizer to reduce the water:binder (w/b) ratio in their
mixes (Naik et al.,1996; Atis, 2003; Siddique, 2004; Duran-Herrera et al., 2011; Huang et al.,
2013; Kayali and Ahmed, 2013; Toledano-Prados et al., 2013; among others), successfully
producing mixes with good workability and practically acceptable early strength. This is why
Aitcin and Mindess (2011, p.138) wrote that superplasticizer’s “appropriate use increase
concrete’s sustainability”. In fact, superplasticizer is regarded as an essential if highly
sustainable concrete is to be achieved (Aitcin and Mindess 2011; Bakash and Reddy, 2013; Santhanam, 2013).

The concern with some of the HVFA studies however is that in order to achieve good rheology with extraordinarily low water:binder (w/b) ratios below the order of 0.3 and sometimes as critically low as 0.13 (e.g. Yazıcı, 2007), so as to produce highly sustainable HVFA concrete with superior strength properties, excess dosage of superplasticizer is used; an act that has been noticed since the early stages of the HVFA concrete research (Ramachandran, 1979). Many studies (Poon et al., 2000; Aydın, et al., 2007; Yazıcı, 2007; Dinakar et al., 2008; Felekoğlu and Sarıkahya, 2008; Chen et al., 2013) have used liquid superplasticizer dosages of between 3% and over 5% of cement by mass despite the normal dosage range being between 0.5% and 2.5% [considering that superplasticizers have similar density to water as shown in Mardani-Aghabaglou et al’s (2013) work] according to The Concrete Institute (2013). This depicts that more than double the recommended dose is sometimes used to achieve practically useful highly sustainable HVFA concrete. Despite claims that excess dosage of superplasticizer may have negative effects on HVFA concrete (Ramachandran, 1979), no study has investigated such effect; especially on the set and hardened concrete properties. Studies have rather concentrated on the effect of different types of superplasticizers on HVFA concrete (Toledano-Prados, 2013; Tkaczewska, 2014). On another front, superplasticizers are quite expensive (Malhotra, 1978) hence excessive use might be infeasible and/or unsustainable in real projects, especially if the gains are minimal and/or losses are many.

This study thus investigates the effect of excess dosage of superplasticizer on the highly sustainable HVFA concrete so that excess dosage can be confidently employed or avoided when necessary. This will increase the understanding of superplasticized HVFA concrete and ensure they are not used in the wrong situations simply because they are more sustainable Low-calcium fly ash was used in the proportions of 50%, 60% and 65% of the total mass of cementitious materials to prepare HVFA concrete mixes. The maximum dosage of superplasticizer and excess dosages were used in different mixes. The effect of this on slump, flowability, compressive strength, flexural strength, tensile splitting strength, and abrasion resistance were investigated.

2.0 Experimental Approach

2.1 Concrete Constituent

The cement employed for the experiment was a commercially available Ordinary Portland Cement strength class 42.5 conforming with CEM I 42.5N (Portland cement) of BS EN 197-1:2011 standard (Table 1). The fly ash used was commercially available low lime fly ash
conforming to BS EN 450–1:2012 standard, class N (Table 1). Graded crushed limestone
with maximum particle size of 16 mm was used as coarse aggregate (Table 2) conforming to
BS EN 12620:2013 standard. Locally available dry sand with maximum particle size of 5 mm
was used as fine aggregate (Table 2) conforming to BS EN 12620:2013 standard. The water
absorption and specific gravity tests for the aggregates were carried out according to BS EN
1097-6:2013 standard. A commercially available liquid superplasticizer which conforms to
BS EN 934-2:2009+A1:2012 was used.

Table 1: Properties of cement and fly ash used.
Table 2: Properties of aggregates used.

2.2 Concrete Mixture Proportion

The main constituents of the HVFA concrete mixes include cement, fly ash, coarse
aggregate, fine aggregate, water and superplasticizer. The mix proportions were determine
based on Malhotra (2002). Four series of concrete mixes were designed with one standing
as a form of control series. The control series comprised of only one mix type, is designated
series 0, was prepared with only cement as binder and without any superplasticizer. The
second series comprised of three mixes of HVFA concrete each containing 50% fly ash as
cement replacement and is designated series 50. The mixes were prepared with fixed
powder dosage (cement + fly ash), sand/coarse aggregate and w/b ratios. For
superplasticizer dosage, the maximum dosage of superplasticizer (i.e. 2.0% of binder by
mass) was used for one mix, while the two other mixes were prepared with 1.5 times (i.e.
3%) and twice (i.e. 4%) the maximum dosage of superplasticizer respectively. Series 60 and
65 similarly comprised of three mixes each, with mixes in the series containing 60% and
65% fly ash respectively. The three mixes in each series contained maximum dosage, 1.5
times and twice the maximum dosage of superplasticizer respectively.

Although effort was made to keep the w/b ratio constant for series 50, 60 and 65, this was
not possible as the mixes with higher fly ash content required more water at maximum
dosage of superplasticizer to achieve acceptable visual workability. Water content was
however successfully kept constant across all series 60 and 65 mixes (see Table 3).

The prescribed maximum superplasticizer dosage was approximately 2% of cement by mass
but as done generally in HVFA concrete studies, this was taken to be 2% of binder (cement
+ fly ash) by mass. The control series was named CG0 (i.e. control group with 0%
superplasticizer and fly ash). In series 50, a mix type named MD2.0F50 will have MD2.0
representing maximum dosage of superplasticizer at 2.0% of binder by mass, and F50
representing the percentage of fly ash content in the binder. In series 60, a mix named ED3.0F60 will have ED3.0 representing excess dosage of superplasticizer at 3.0% of binder by mass and F60 representing the percentage of fly ash content in the binder. The details of the concrete mixtures are presented in Table 3.

One controversial aspect of research on effect of superplasticizer on HVFA concrete is the pattern of spread of w/b ratio across the mix samples. Although the aim of study should be the main deciding factor, comparable studies in the past have used different concepts. Some studies (e.g. Al-Amoudi et al. 2006; Mardani-Aghabaglou et al 2013; Tkaczewska, 2014) investigated the effect of different types of superplasticizer and rightly kept a constant w/b ratio across all mixes while each type of superplasticizer was applied to the mixes using a dosage that resulted in a set target slump. However Toledano-Prados et al., (2013) performed similar experiments using constant w/b ratio and superplasticizer dosage, leaving the mixes to have real varying slumps.

Studies that are more similar to this study, i.e. that have used a single type of superplasticizer to check the effect of properties of superplasticizer on properties of concrete have not been consistent either. Some studies (e.g. Felekoğlu and Sarkahya, 2008; El-Didamony et al. 2012; Bouharoun, et al 2013; Tkaczewska, 2014) have tried to consider the real life situation where a target slump is set, and superplasticizer is only increased in order to reduce water content, hence they reduced w/b ratio of mixes as they increased superplasticizer dosage. The idea is to to give their experiment more practical value. However, this process makes it hard to know the real effect of the superplasticizer as the varied w/b ratio will also have effect on the results. Morin et al. (2001) performed a similar experiment. They used constant w/b ratio an varied only the superplasticizer content. This ensured that the real effect of the superplasticizer of the concrete was gotten. This is considered to be very experimental but it actually achieves the aim of the study better hence its adoption (i.e. constant w/b ratio for mixes with the same fly ash content and varying superplasticizer dosage) in this study (see Table 3).

Table 3: Proportion of concrete constituents present in the mixes.

2.3 Preparation and Casting of Specimen

Concrete mixing and production was done according to BS EN 206:2013. A laboratory mixer was employed for mixing. A target slump of between 50 mm and 90 mm with a maximum allowable deviation of ±30 mm was set for all mixes as stipulated in BS EN 12350-2:2009 and several trial mixes were completed. During actual sample production, an initial w/b ratio
of 0.2 was used to start mixing. After a short period of about three minutes, superplasticizer mixed with ‘0.03 w/b ratio’ quantity of water was added, bringing total w/b ratio to 0.23. This timing and mixing with water ensured the superplasticizer had an optimal effect on the mixes (Chiocchio and Paolini, 1985; Malier, 1992; Fisher, 1994; Tkaczewska, 2014). With knowledge from trial mixes, extra water was added until a visual inspection revealed acceptable workability. This process was done for the mixes containing maximum dosage of superplasticizer only. The w/b ratio achieved for a mix with maximum superplasticizer dosage was simply repeated for the two remaining mixes in the same series (i.e. mixes with excess dosage of superplasticizer) to allow a fair assessment of the effect of superplasticizer dosage.

Concrete specimens of 100 mm diameter by 200 mm height were cast for the compressive strength test. Square beams of 100 mm x 100 mm x 350 mm length were produced for flexural strength, cylindrical specimen of 150 mm diameter and 300 mm length for tensile splitting strength and 500 mm x 500 mm x 50 mm specimens for abrasion test. Three specimens were produced for each testing age. All specimens were demoulded after 48 hours and placed in a temperature regulated curing room at 25°C.

2.4 Fresh Concrete Tests

To determine the workability and consistency of the mixes, slump test to BS EN12350-2:2009 was carried out on each of the mixes and the results recorded. Also, flow table test to BS EN12350-5:2009 was carried out on each of the mixes and the results recorded.

2.5 Hardened Concrete Tests

The compressive strength of the 100 mm diameter by 200 mm height cylindrical specimen was determined according to BS EN12390-3:2000 using a ‘Controls’ compressive strength machine. The load was applied slowly at a rate of 0.2 to 0.4 N/mm². The flexural strength test was performed on the 100 mm x 100 mm x 350 mm square beams in accordance with BS EN 12390-5:2009 while tensile splitting strength test was performed on the 150 mm diameter by 300 mm length cylindrical specimen in accordance with BS EN 12390-6:2009. The abrasion resistance test was performed on the 500 mm x 500 mm x 50 mm specimens in accordance with BS EN 13892-4:2002 and BS EN 13892-1:2002.

3.0 Experimental Results And Discussion

3.1 Fresh Concrete Properties

The results of the fresh concrete tests are given in Table 4. The specified upper limit of 0.3 w/b ratio for HVFA concrete according to Malhotra and Mehta (2002) was not achieved with
the prescribed maximum dosage of superplasticizer. This clearly explains why many studies end up using excess dosage. This might also be due to the type of superplasticizer being used as some studies have successfully achieved very low w/b ratio with not too much superplasticizer dosage (e.g. Huang et al., 2013; Kayali and Ahmed, 2013). Tables 3 and 4 clearly show a reduction in slump value for mixes with higher content of fly ash despite such mixes having equal or higher water/binder ratio. This means increase in fly ash content in HVFA concrete mixes results in increase in water demand as confirmed in many previous studies (Malhotra 2002; Malhotra and Mehta, 2002; Mehta, 2004). Hence the concept of having the highest slump value for the HVFA concrete mix with the highest percentage of fly ash content (75%) when w/b ratio and superplasticizer dosage were kept constant across some HVFA concrete mixes, as shown in some studies (e.g. Duran-Herrera et al., 2011; Balakrishnan and Awal, 2014), is to an extent incomprehensible to the authors of this study.

Table 4: Fresh concrete tests results.

In a similar case in Huang et al’s. (2013) work where superplasticizer dose was kept constant across mixes and a HVFA concrete mix with higher fly ash content achieved a relatively lower w/b ratio and higher slump, the contentious mix contained a relatively lower fine aggregate content with a reduction of about 60%; this reduction at least leaves the chance for speculation as probably being the reason behind the achievement.

It appears from the results that using excess dosage of superplasticizer helps to reduce the water demand of the mixes further than the prescribed maximum dosage, depicting that excess dose does not have a negative effect on water demand of HVFA concrete mixes. Nevertheless, the slump and flow table test results make it appear that the superplasticizing effect per volume of superplasticizer reduces as the dosage gets more excessive. However, it is very hard to estimate the proportionality of reduction of the superplasticizing effect to excessiveness of dosage from the results since reduction in slump and/or flow table values against increase in superplasticizer dose are not uniform across series 50, 60 and 65 mixes. This makes it hard to identify the probable ‘break point’ dosage at which the superplasticizing effect starts diminishing. Another point is that liquid superplasticizers have a certain percentage of water content, whose effect is generally neglected in most studies, thus a large increase in dosage can effectively result in increased w/b ratio. For example, Poon et al. (2000) reported the superplasticizer used in their research to contain a water content of 61.5%, this means a superplasticizer excess dose of 4% of binder or 4 litres per 100 kg of binder can result in as much as over 2 litres or kg of water per 100 kg of binder, or over 8 kg/m³ of water where 400 kg/m³ of binder is used. Hence the modest
superplasticizing effect applicable at excess dosage might even be as a result of increased w/b ratio rather than any chemical action/reaction.

Although the target slumps set for the mixes were achieved as a result of experience from trial mixes, it was not achieved with the required water/binder ratio of 0.3 or less. The target range with a minimum target of 50 mm was selected so as to allow the use of as small amount of water as possible for the purpose of improving mechanical properties. The flow table test also gave satisfactory results. The pattern differences in mixes flows are similar in proportions to the slump test results.

Like in other studies (Huang et al., 2013; Kayali and Ahmed, 2013), the results show that increase in fly ash content causes a slight reduction in unit weight when mixes with the same superplasticizer content of 3% or 4% are compared across the three series of HVFA concrete mixes. The fact that series 0 mix has a higher unit weight than all the fly ash concrete mixes confirms the reduction of density due to presence of fly ash. However, there seem to be ambiguity in unit weight results when mixes with 2% superplasticizer content are compared across series 50, 60 and 65 as no clear trend can be deciphered. The initial claims can thus not be absolutely made. Nonetheless, it makes sense for the weight of mixes to reduce with increment in fly ash content since batching was done by weight and cement has a higher density than fly ash (Sear, 2001). The increase in unit weight due to increase in superplasticizer dosage when comparing mixes in the same series is expected since all other constituent materials’s weights were kept constant.

3.2 Compressive strength

The compressive strength test was carried out on the specimens at the ages of 7, 28, 52, 91 and 365 days. The results are presented in Table 5 and Figures 1 and 2. Clearly, the compressive strength of all mixes increased with age (Figures 1 and 2). Each chart in Figure 1 compares the compressive strength of mixes with the same dosage of superplasticizer but different percentage of fly ash content (note that series 60 and 65 mixes have the same w/b ratio), and the CG0 control mix.

Table 5: Results of the compressive strength test (MPa) of all mixes at various ages.

As expected, the plain cement control mix i.e CG0 gained over 90% of its one year strength after 28 days. Although hydration of cement continued beyond 28 days, it was at a minimal rate leading to only very slight increase in strength over time (Figure 1). The HVFA mixes strangely followed a similar trend to that of CG0 mixes with no significant gain in strength in
the later days. This is not too surprising since this study's necessary experimental
requirement, which is to keep the w/b ratio constant across mixes with the same percentage
of fly ash content and meet a certain target slump, led to what can be referred to as excess
w/b ratio for HVFA concrete. The maximum w/b ratio required to achieve good strength in
HVFA concrete mixes is 0.3 according to Malhotra and Mehta (2002). Many studies have
even had to use smaller w/b ratio to achieve good strength for HVFA mixes (e.g. Poon et al.,
2000; Aydin et al., 2007; Yazici, 2007; among others).

Figure 1: Compressive strength versus age of mixes with the same superplasticizer
percentage.

Figure 2: Compressive strength versus age of mixes with equal percentage of fly ash
content.

It is clear from the charts (Figure 1) 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. It can however be noticed that the the
activation of fly ash had started before one year (between 91 and 365 days) since mixes with
more fly ash have a higher strength at this age. The fly ash activation in, and strength gain
of, the HVFA concrete mixes will continue beyond the 365 days limit used in this study and
the mixes 'might' end up gaining more strength than the CG0 mixes. However, as previously
noted, the ultimate solution is to use a very small water/binder ratio if HVFA concrete is to be
of good early and overall strength (Malhotra, 1978; Poon et al, 2000; Malhotra 2002;
Malhotra and Mehta, 2002; Mehta, 2004; Duran-Herrera et al., 2011; Balakrishnan and Awal
2014; and more). It is only with enough early and better overall strength that contractors can
be easily persuaded to make more use of the highly sustainable HVFA concrete in real life
projects.

Each chart in Figure 2 compares mixes with equal fly ash content and w/b ratio but different
superplasticizer dosage. The charts show that increase in superplasticizer leads to slight
reduction in early strength of HVFA mixes (series 50, 60, and 65). This effect is probably due
to the water content of the liquid superplasticizer which might have in turn led to a slight
increase in w/b ratio. The charts also show similar mixes with different superplasticizer
dosage to have an almost equal overall strength. This depicts that excess dosage (twice the
recommended dose at most) of superplasticizer has no long term effect on strength of HVFA
cement. The results show that excess dosage can only be really useful strength-wise if it
will help reduce w/b ratio since increasing the dose at a constant w/b ratio has no positive effect on the concrete but a negative effect on early strength.

3.3 Flexural strength

Pavement concrete and structural concrete members like beam, which are generally subjected to bending when in use, make flexural strength (or modulus of rupture) very important. This is why flexural strength is one of the principal factors in concrete pavement. Like for the compressive strength, the flexural strength test of the specimens were carried out at the ages of 7, 28, 52, 91 and 365 days. The results are presented in Table 6 and Figure 3. Each chart in Figure 3 compares the flexural strength of similar mixes with different superplasticizer doses i.e. mixes in the same series are compared.

The flexural strength of all mixes increased with age. Like in the case of compressive strength, the rate of gain of flexural strength of the control mix CGO expectedly tailed off drastically at the higher ages of 56, 91 and 365 days, while the HVFA concrete mixes (series 50, 60 and 65) did not perform much better at later ages. This, as initially explained, is due to the use of a w/b ratio higher than required for high strength for the series 50, 60 and 65 mixes. Further, from Table 6 and Figure 3, it can be deciphered that an increase in superplasticizer causes a reduction in flexural strength. This effect tails off as the concrete ages and is very minimal at later ages when considering series 50 and 60. The reduced early flexural strength for mixes with high dosage of superplasticizer might again be due to the superplasticizer's water content since the difference in early flexural strength of similar mixes with different superplasticizer dose is small and the long term (one year) flexural strengths are practically equal. Overall excess dosage of superplasticizer cannot be said to have had any decisive effect on the flexural strength of the HVFA concrete mixes, at least not from the results gotten in this study.

Table 6: Flexural strength (MPa) test results of all mixes at various ages.

Comparing series 60 and 65 which have the same w/b ratio, it can be deduced from Table 6 (last column) that increase in fly ash seem to cause reduction in overall flexural strength. In all, no HVFA concrete mix achieved the minimum 4.0 MPa 28-day flexural strength requirement of the British Airport Authority for pavement construction concrete (Calverley, 1977) or superior flexural strength compared to the CG0 control mix at later ages. Obviously a lower w/b ratio will be needed to achieve this, however that is not the aim of this study.
3.4 Tensile Splitting Strength

Tensile splitting strength test of the specimens were carried out at the ages of 7, 28, 91 and 365 days. The results are presented in Table 7 and Figure 4. Each chart in Figure 4 compares the tensile splitting strength of similar mixes with different superplasticizer doses i.e. mixes in the same series. The trend in the result is quite similar to that of the flexural strength. This is expected as they are both measures of the tensile strength of concrete. The splitting tensile strength of all groups increased with their ages. The rate of strength gain for control group CG0 drastically reduced at later ages between 91 and 365 days. The HVFA concrete mixes i.e. series 50, 60 and 65 did not gain a lot of tensile splitting strength at these later stages either as the mixing water was more than required to get high strength results. From Table 7 and Figure 4, a reduction in tensile splitting strength can be the result of an increase in superplasticizer dose. This response diminishes as the concrete ages and becomes very little and almost negligible at later ages, especially at 365 days.

Table 7: Tensile splitting strength (MPa) test results of all mixes at various ages.

As shown in Table 7 only two mixes, CG0 and MD2.0F50, met the minimum required 7-day tensile splitting strength of 1.85 MPa specified for road construction concrete by the British Department of Transport (Department of Transport, 1976), although ED3.0F50 and MD2.0F60 were close at 1.80 MPa. MD2.0F50 is the mix with the least fly ash content and superplasticizer dosage. This might signal that an increase in fly ash content or superplasticizer dosage can both cause an adverse effect on HVFA concrete mixes. The negative fly ash effect can be deciphered by comparing the series 60 mixes to corresponding series 65 mixes. The only difference between these mixes is the fly ash content and series 60 mixes, with lower fly ash content, have relatively higher tensile strengths. Judging by how small the effect of superplasticizer is, and its diminishing effect at later ages, on the mixes the dosage of superplasticizer cannot be strongly concluded to have a definitive effect on the tensile splitting strength of the HVFA concrete mixes.
Figure 4: Tensile splitting strength versus age.

3.5 Abrasion Resistance test

The abrasion resistance tests were carried out at the ages of 28, 91 and 365 days. In each case, the abrasion machine was operated on the specimens until 2850 (±5) revolutions were completed as specified in BS EN 13892-4:2002. This took about 15 minutes. The results of the tests are presented in Table 8 and Figures 5 and 6. Each chart in Figure 5 compares the abrasion or wear depth (µm) of mixes with equal superplasticizer dosage but different percentage of fly ash content while those in Figure 6 compare mixes with equal percentage of fly ash content but different superplasticizer dosage i.e. mixes in the same series.

Table 8: Wear depth (µm) of all the mixes at the ages of 28, 91 and 365 days.

As expected, the abrasion resistance of all mixes improved with age. Taking cognisance of the fact that the only difference between series 60 and 65 mixes is the fly ash content, the results show that increase in fly ash content in HVFA mixes lead to poorer abrasion resistance at all ages up to a year (Figure 5). This fact is also proven in other studies (e.g. Naik et al., 1995; Vassou et al., 2002) though some authors have works that show otherwise (e.g. Atis, 2002). While the rate of increase in abrasion resistance of the control mix CG0 seem to be somewhat steady between 28 and 365 days, the rate of increase in abrasion resistance of HVFA concrete mixes reduced between 91 and 365 days compared to between 28 and 91 days (note that the higher the abrasion value, the lower the abrasion resistance of the mix).

From Figure 6, where mixes in the same series are compared, it is very clear and evident that excess dosage or increase in dosage of superplasticizer causes poorer abrasion resistance. The reason for this cannot be established from these results hence further research is needed in this area. Excess superplasticizer ‘might’ also be responsible for the reduced rate of gain of abrasion resistance of HVFA concrete mixes between 91 and 365 days. Generally, this result signifies that too much superplasticizer should be avoided in concrete mixes to be used in applications like industrial floors where wear/abrasion resistance is of vital importance. If early HVFA concrete strength is needed and the desired w/b ratio cannot be achieved with normal dose of superplasticizer, then rapid hardening cement should be employed as established by Malhotra and Mehta (2002). It also signifies that HVFA concrete generally might not be too fit for applications like industrial floors where
wear/abrasion resistance is of vital importance since fly ash also has a negative effect on abrasion resistance.

Figure 5: Wear or abrasion depth (µm) versus age of mixes with the same superplasticizer percentage.

Figure 6: Wear or abrasion depth (µm) versus age of mixes with equal percentage of fly ash content.

4.0 Effects of Study on Sustainability of Concrete

Concrete remains the most used manmade material yet it is highly unsustainable in its simplest form. Its unsustainable nature is due mainly to a major constituent material i.e. cement, whose demand by the year 2020 is expected to be 180% higher than in 1990 (Humphreys and Mahasenan, 2002). Cement production consumes a large amount of natural resources and energy and causes a huge amount of CO₂ emission leading to environmental degradation. Reducing the consumption of cement by partly replacing it with a more sustainable material is obviously a very sustainable action. The replacement material i.e. fly ash, being a troublesome landfill waste produced in millions of tonnes yearly, makes such action even further sustainable. The push for increased use of fly ash led to research that brought about HVFA concrete. However, the main problem of HVFA concrete is its very slow rate of strength gain. This has hampered the level of use of HVFA concrete on real projects, thus impeding the sustainability gains made in concrete experimental research. Research has proven that using a very small w/b ratio, normally achieved through the use of large amounts of superplasticizer, can mitigate the slow rate of strength gain of HVFA concrete. However there is need to establish the effect of these large amounts of superplasticizer on HVFA concrete before they are discovered on practical projects where contractors/users can really get disappointed and lose confidence in a material that has not even gained enough confidence in the first place. This is exactly what this study has investigated.

Findings have shown that large amounts or excess dosage of superplasticizer has no substantial effect, negative or positive, on the compressive, flexural and tensile splitting strengths of HVFA concrete. This means that it is okay to use large amounts of superplasticizer in order to ensure the highly sustainable HVFA concrete gains enough early strength to allow usage on real life projects where compressive, flexural and tensile splitting strengths are of importance. However, findings also showed that large amounts of highly superplasticizer reduce abrasion resistance of HVFA concrete hence they should not be
used for applications such as industrial floors where abrasion resistance is of dire importance. The discovery in this study will ensure that contractors/users do not use superplasticized HVFA concrete for wrong applications (e.g. industrial floors) and end up getting disappointed. Such action would erode the modest confidence users have in HVFA concrete and hamper the real life use of the highly sustainable material. This study will thus ensure that the practical use of the highly sustainable HVFA concrete is not hampered through wrong and uninformed use.

Further, the findings depict that if there is a strong desire to use sustainable fly ash concrete on an industrial floor project for example, then the fly ash content and superplastcizer contents can be reduced to a minimum. This will ensure that superplasticizer is not unnecessarily used. Since superplasticizer is made from raw materials consuming chemicals through carbon emitting industrial process, avoiding its unnecessary use is in itself is an act that supports sustainability and reduces environmental degradation.

5.0 Conclusion

Since it is quite common for researchers to use excess dosage of superplasticizer to achieve the desired very low w/b ratio in sustainable HVFA concrete so as to obtain early strength without reporting on the effects of the excess dosage, this study investigated the effects of such excess dosage on HVFA concrete properties. The results of the study have been presented in the body of this work and the conclusions that can be drawn from the results are given below:

1. Excess dosage of superplasticizer results in a decrease in abrasion resistance of sustainable HVFA concrete. Likewise, increase in percentage of fly ash content results in poorer abrasion resistance of HVFA concrete.

2. Although HVFA concrete, which is normally prepared with high dosage of superplasticizer, is highly sustainable, it is not the best for applications like industrial floors where wear/abrasion resistance is of vital importance since both fly ash and superplasticizer have negative effects on abrasion resistance.

3. Excess dosage of superplasticizer, compared to prescribed dosage, can help to increase workability in terms of slump and flow of HVFA concrete.

4. Excess dosage of superplasticizer has no quantifiable effect, positive or negative, on the compressive strength, flexural strength and tensile splitting strength of HVFA concrete.
5. When excess dosage of superplasticizer is used, the superplasticizing effect per volume reduces as more dose is added.

6. With ‘not very low’ w/b ratios as used in this study, HVFA concrete mixes will struggle to meet the minimum required compressive, flexural and tensile splitting strengths of various standards.

7. When batching is done by weight, HVFA concrete mixes will have lesser unit weight compared to cement only mixes because fly ash has a lesser density compared to cement.

8. Increase in fly ash content in HVFA concrete mixes results in reduced overall flexural strength, tensile splitting strength and abrasion resistance.

9. Good early and long term (one year to be specific) compressive strength cannot be achieved for HVFA concrete if ‘very’ low w/b ratio is not realised with the aid of superplasticizer.

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