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Evaluating the performance of high-volume fly ash (HVFA) concrete, for South African fly ash

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Abstract : *Due to the benefits provided by the usage of FA in concrete, the usage of HVFA concrete is increasing within the concrete industry. This study looked at the effects of increasing the content of FA in concrete, beyond the conventional 30% amount, to find an optimum amount suitable for use in concrete structures, without compromising the quality of concrete. Concrete mixes of 25MPa, 35MPa and 50MPa with FA partially substituting the cement at 30%, 40%, 50% and 60%, were produced and numerous concrete properties were evaluated in a laboratory environment, to determine an optimum amount of HVFA that can be used and still obtain better or comparable concrete to ordinary concrete. Concrete testing for compressive strength, durability, slump, setting time and drying shrinkage was performed at laboratories over a period of one year. Also a cost comparison between the ordinary concrete and FA concrete was done. Test results showed that HVFA concrete can perform well in structures with good compressive strength and durability result even if the amount of cement is less than of fly ash. It can also be economical to utilize HVFA concrete, especially in larger project.*

Keywords: *Concrete, compressive strength, durability, fly ash, HVFA*

I. Introduction

The usage of pozzolanic materials in concrete dates back to the Roman times in structures such as the Pantheon and Pont du Gard and they are still standing today [1]. Fly ash (FA) is considered a pozzolanic material, as it is a siliceous/aluminous material which, and in itself, possesses little or no cementitious value, but when mixed with lime (Calcium Hydroxide) and water, form cementitious compounds. FA has been incorporated in the concrete as a partial replacement of cement due to its pozzolanic properties which it has been said to improve the quality and properties of concrete. FA is an industrial by-product that is normally consigned to landfills and the re-use of it as cement extenders also provides an immediate benefit for the environment.

Each ton of FA used in cement, or blended into the concrete mix, saves approximately one ton of CO2 emitted during the production of Portland [2]. It has been estimated that in the last decade, the use of FA (FA) products by the South African cement and construction industries has saved the country over 6 million tons of harmful greenhouse gas emissions [3]. In the USA, Leadership in Energy and Environmental Design (LEED) points, which are points awarded based on environmental performance, are available for any mixture that replaces up to 40 percent of the cement in concrete with FA [4].

1.1 Background: To increase the sustainability of concrete, cement producers are increasingly producing blended cements, in which some of the Portland cement clinker is replaced by substantial amounts of supplementary cementitious materials (SCMs) or fillers [5]. FA has been extensively used worldwide as an extender in blended cements. The National Building Research Institute (NBRI) of the Council for Scientific and Industrial Research (CSIR) did the first investigation into the use of South African FA as a cement extender in 1955 and research into FA and its use is still on-going [6]. Although there has been a usage of concrete with high FA volume, in general practice the 30% FA replacing cement in concrete is considered suitable for durable concrete, and the specifications limit the FA usage to 30%.

It is well documented around the world that the FA concretes perform better than pure cement in providing workability and durability of concrete. An increase of the standard 30% FA amount can result in better performing concrete and consequently more relief on the environment. In some areas of construction, FA is used extensively beyond 50% with positive results. Such concrete is termed high-volume fly ash (HVFA) concrete.

1.1.1 Case Studies : In recent history in the US state of Florida, a housing project in Gainesville, Madeira employed the usage of high volume FA successfully to promote resource-efficient construction. Approximately 33 yards of 60% Class F FA concrete mix was used in the construction of exterior walls and approximately 18 tons of FA was used to replace cement, which reduced CO2 emissions into the atmosphere by approximately 18 tons [7]. Recently in Rustenburg, South Africa, in a Bus Rapid Transit (BRT) project, the Engineers opted to replace 60% of cement with FA [8]. The project was hailed as a great success and it played a big role in mitigating climate change.

1.2 Effects of FA on Concrete Properties : Researches done globally show that the use of FA as a partial replacement in concrete tends to reduce the early strength up to 28 days, but improves the ultimate strength (after more than a year) due to the pozzolanic reaction. Due to the spherical shape of FA particles and their extreme fineness, the greater the percentage of FA in the concrete paste, the better is the lubrication of aggregates and the flow of concrete. The use of FA has been proven to reduce the amount of water needed to produce a given slump. The cement/water ratio could be reduced by 2% to 10% [2].

In concrete, lime remains intact and over time it would be susceptible to the effects of weathering and loss of strength and durability [9]. FA reacts with lime to create more Calcium Silicate Hydrate (CSH), produced during hydration of cement and water, resulting in a less permeable and more durable concrete. This study was undertaken to evaluate if the increase of FA volume in concrete can have positive effects on concrete properties and what would be the optimum amount of FA that could partially replace cement without compromising the integrity of the concrete. This paper contains a summary of results from the dissertation research work, where the effects of FA on concrete properties such as workability, compressive strength, durability and cost are evaluated.

II. Scope

1.3 Methodology : Three grades of concrete mixes (25MPa, 35MPa and 50MPa) were designed with FA partially substituting cement at four levels of 30% (control), 40%, 50% and 60%. Cube specimens of 100 x 100 x 100mm were made and tested at the DUT laboratory for compressive strength from 1 day to 1 year period as per [10]. Other test specimens, for the 35MPa mix were made at the Contest laboratory for the durability index testing in terms of Oxygen Permeability Index (OPI), Chloride Conductivity and Water Sorptivity as outlined in [11]. Slump tests were performed on these mixtures for the determination of workability in terms of consistency. The setting time and initial drying shrinkage of concrete was also determined under laboratory conditions**.**

1.4 Materials Used : The materials used were sourced locally, in Durban, with the cement and FA originally from the Gauteng region, in South Africa. The unclassified FA was obtained from Lafarge and 52,5N Ordinary Portland Cement (OPC) was bought from a local supplier. The 9,5mm stones used were sourced from the local Lafarge quarry and the fine aggregates (river sand) were sourced from a local hardware store. Ordinary tap water was used for mixing. No admixtures such as plasticizers or retarders were used in the experiment**.**

III. Results and discussion

The mix proportions for all the mixes produced at the laboratory are shown in Table 1 below.

Table 1: Mix proportions for the concrete mixtures

Mix (Mpa/FA%)	W/C	Water (*l*)	Tot. Binder (kg)	Cement (kg)	FA (kg)	Stone (kg)	Sand (kg)
25/30	0,6	210	350,00	245,00	105,00	850	870,00
25/40	0,6	210	350,00	210,00	140,00	850	870,00
25/50	0,6	210	350,00	175,00	175,00	850	870,00
25/60	0,6	210	350,00	140,00	210,00	850	870,00
35/30	0,5	210	420,00	294,00	126,00	850	800,00
35/40	0,5	210	420,00	252,00	168,00	850	800,00
35/50	0,5	210	420,00	210,00	210,00	850	800,00
35/60	0,5	210	420,00	168,00	252,00	850	800,00
50/30	0,37	200	540,54	378,38	162,16	850	689,46
50/40	0,37	200	540,54	324,32	216,22	850	689,46
50/50	0,37	200	540,54	270,27	270,27	850	689,46
50/60	0,37	200	540,54	216,22	324,32	850	689,46

1.5 Workability : The slump tests were performed on the 35MPa concrete mixtures at the laboratory as per [12], and the results are shown in Table 2 which shows the plastic properties, for the 35MPa mixtures, obtained in the laboratory.

Table 2: Plastic properties for the 35Mpa concrete mixtures

Description	35Mpa/0FA	35Mpa/30FA	35Mpa/40FA	35Mpa/50FA	35Mpa/60FA
FA (%)	0	30	40	50	60
Slump (mm)	55	70	85	85	75
Air content (%)	0,5	2,1	2,2	2,0	1,3
Density (kg/m^3)	2295	2295	2296	2282	2295

From the results it is observed that with the increase of the FA volume, the plastic properties, especially the slump, get affected. The increase in FA content resulted in concrete with slightly higher slump, especially compared to the concrete containing no FA. As mentioned, this may be attributed to the spherical shape of the FA particles which promotes cohesion in the concrete. This increased slump means that the concrete with higher FA content can result in more workable concrete with good consistency.

1.6 Time of Set : The determination of setting time for 35MPa concrete mixes was done at the laboratory and yielded the results shown in Table 3. The setting time results show us that by increasing the FA content, the concrete takes longer to set. The ordinary concrete took the least time to set than the FA mixtures. This is consistent with the literature as the heat of hydration is lowered when the cement content is decreased, thus making the concrete set slower than ordinary.

Table 2: Setting time for the 35MPa mixtures at a laboratory

Mix Description	Lab. Reference	Initial Setting (Hrs:min)	Final Setting (Hrs:min)
35/9,5-0%FA	CT1148	7	8:45
35/9,5-30%FA	CT1032	8:40	12:24
35/9,5-40%FA	CT1039	-	13:47
35/9,5-50%FA	CT1048	10:40	13:28
35/9,5-60%FA	CT1054	11:24	14:38

1.7 Compressive Strength : The specimens made from the DUT laboratory were tested for compressive strength from 1 day to 1 year of age, with the average of three cube specimens taken as the final results in accordance with [12]. The compressive strength results of the specimens are represented in Fig. 1, 2 and 3.

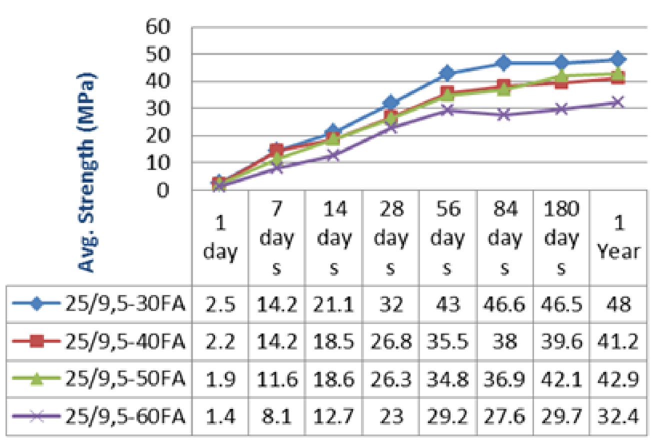

Figure 1: Compressive Strength results for the 25MPa concrete mixtures

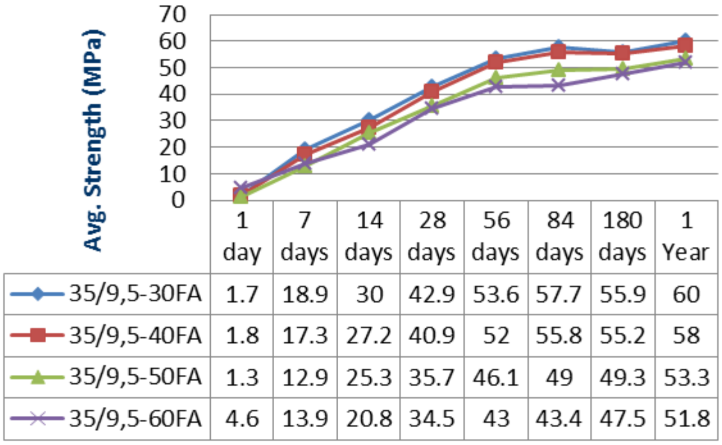

Figure 2: Compressive Strength results for the 35MPa concrete mixtures

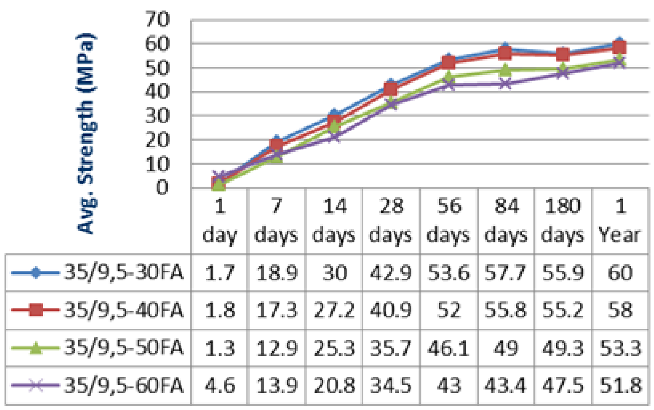

Figure 3: Compressive Strength results for the 50MPa concrete mixtures

The results show that the control mixture, with the 30% FA content, gained higher strength than the other FA mixtures. All the mixtures achieved acceptable compressive strength results after 28 days. Even though the higher mixtures gained lower strength at 28 days, the strength gained at 56 days is very impressive for all the mixtures. It can be seen that over a period of a year, the mixtures continued gaining strength, with all the mixtures gaining between 28% and 72% more, of the specified 28-day strength. The results show that the FA can partially substitute cement beyond 50% without compromising the compressive strength of structural elements.

1.8 Durability : The three concrete durability index tests, namely, Oxygen Permeability Index (OPI), Water Sorptivity and the Chloride Conductivity, were performed on the grade 35MPa mixtures at the Contest laboratory. These tests give a relative indication of the resistance of the cover concrete to the ingress of chlorides and/or carbon dioxide. Table 4 shows the South African acceptable Durability Indices limits.

Table 4: Acceptance limits for durability index tests [11]

Acceptance Criteria		**OPI (Log scale)**	**Sorptivity (mm/√h)**	**Cl Conductivity (mS/cm)**
Laboratory concrete		>10	<6	<0,75
As-built Structures	Full acceptance	>9,4	<9	<1.00
	Conditional acceptance	9,0 to 9,4	9 to 12	1,00 to 1,50
	Remedial measures	8,75 to 9,0	12 to 15	1,50 to 2,50
	Rejection	<8,75	>15	>2,50

1.8.1 Oxygen Permeability Test (OPI) :The tests for OPI were performed for the 35MPa concrete mixtures after 28 days, and the results are graphically represented in Fig.4. From Fig. 4 is it observed that after 28 days curing period the lower FA mixture (30%)

obtained best results, but the margin between the mixes is very small, with the 40% FA mix obtaining almost similar results. All the mixtures obtained very good results as the OPI values are way above 9, 4.

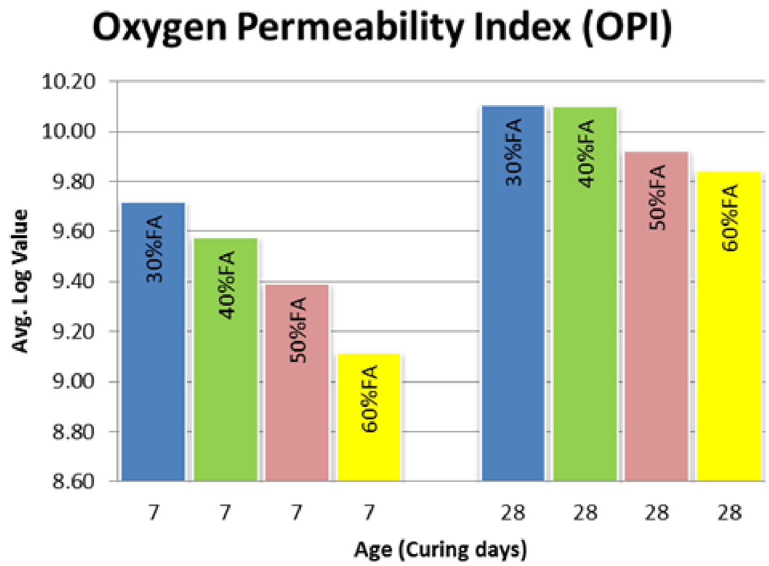

Figure 4: OPI 28-day test analysis

1.8.2 Water Sorptivity Test :The water sorptivity test results for the 35MPa/9,5mm mixes with different FA percentage after 28 days of water curing are represented in Fig.5. The results show that the water sorptivity results are very close after 28 days as illustrated in Fig.5, with the 30% FA mix having the lowest value. The lowest FA mix has the best sorptivity results overall, but all the mixes have fairly good results after 28 days as they average below 11mm/√h. Due to the continuous pozzolanic reaction of FA in concrete, it is expected that the results will improve with age.

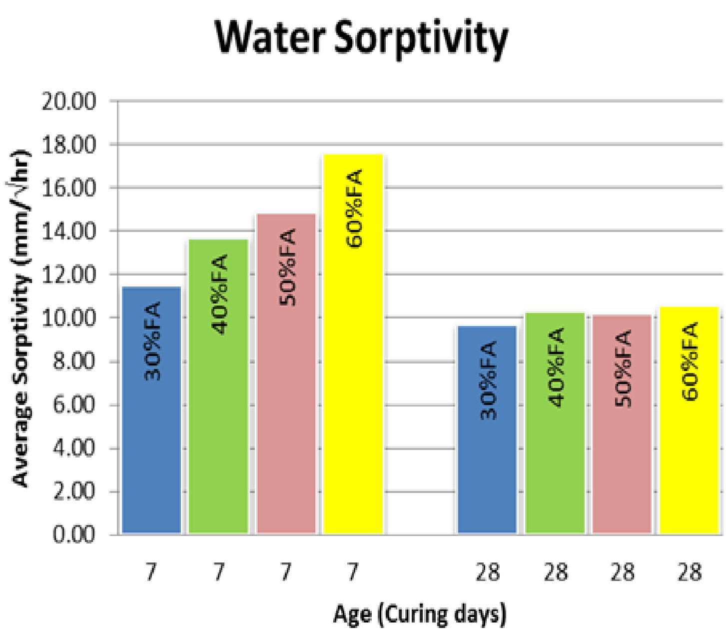

Figure 5: Water Sorptivity 28-day test analysis

1.8.3Chloride Conductivity Test : Fig.6 shows a representation of the Chloride Conductivity test results of the different FA content in the 35MPa/9,5mm concrete mixtures after 28 days of curing. The figure shows that with the increase of FA content (the 50% and 60% FA mixtures) the chloride conductivity improves, with the higher FA mixtures obtaining results between 1,0 and 1,5mS/cm while both the 30% and 40% FA mixtures obtained poor but acceptable results, above 1,5mS/cm.

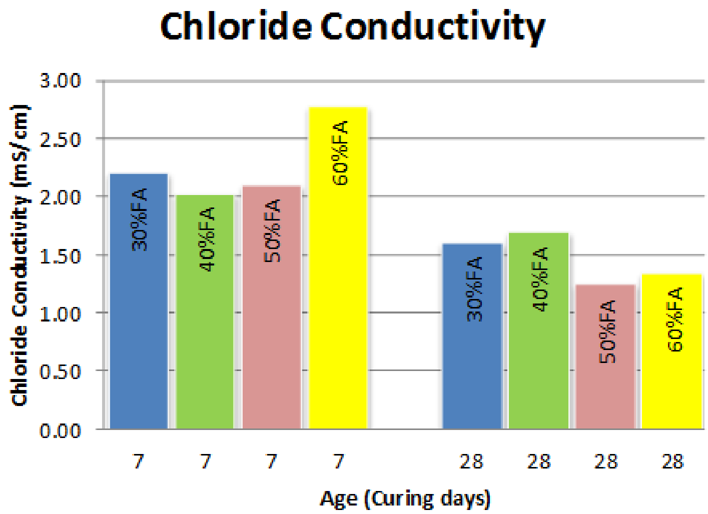

Figure 6: Chloride Penetration 28-day test analysis

The overall durability index results obtained show that the concrete with high FA content can get better and acceptable durability results as illustrated in the OPI and Chloride Conductivity tests. The higher FA mixtures (50% and 60%) obtained better Chloride Conductivity results than the lower, 30% and 40%, which is very beneficial for structures exposed to constant harsh conditions.

1.9 Initial drying shrinkage : In this study the testing for initial drying shrinkage was conducted by measuring the shrinkage of four 35MPa concrete mixtures with FA content of 30%, 40%, 50% and 60%.The concrete linear shrinkage of concrete is measured in accordance with SANS 6085 specifications. Fig. **7**

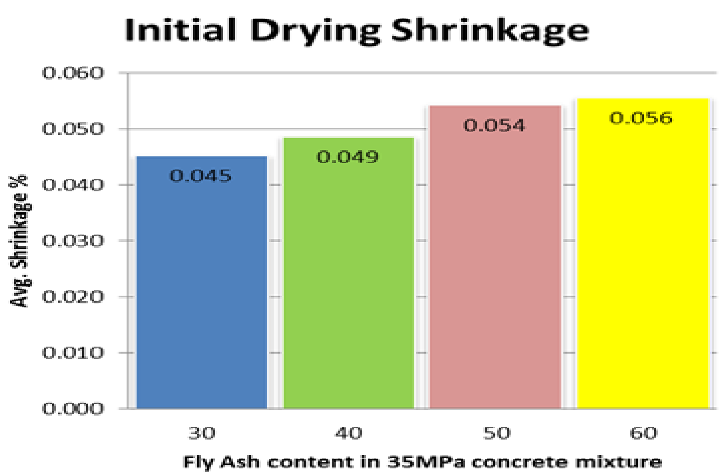

Figure 7: Initial drying shrinkage results for 35MPa concrete mixtures with different FA content

Analysis of a limited number of results shows that most results fall within the range 0.02% to 0.065%. The mean value was approximately 0.045%. It is observed that the drying shrinkage increased with increased FA content. Even though this is not desirable, but the results are within acceptable limits.

1.10 Cost Comparison : For each grade on concrete mixture the cost variation is relatively proportional to the amount of cement substitution by FA. From the materials used in this study the cost of FA ranges between 6 – 12% of the cost of OPC, excluding logistical costs. The cost of the binder can therefore be evaluated according to the price of equivalent cement content by using formula (1), as derived by [13]:

$$C = B(1-0,8*FA/B) \quad (1)$$

Fig.8 shows the cost comparisons between all the concrete mixtures at different levels of cement substitutions. The increase in the FA content decreases the total cost of the mixture per cubic meter, in terms of the binder. In higher W/C mixtures, the savings range from 26 - 46% per m³, where in lower W/C mixtures saving can range from 30 - 55% per m³.

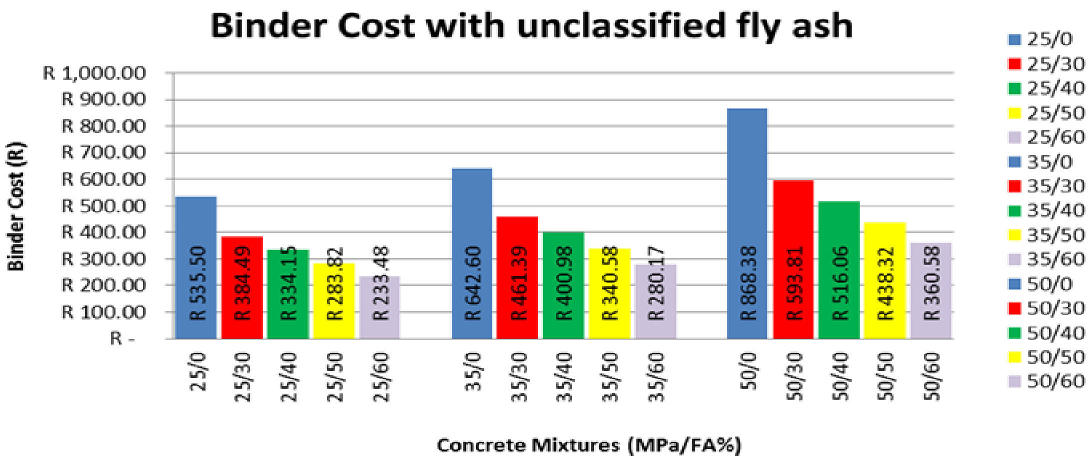

Figure 8: Cost comparisons for mixtures with unclassified FA

IV. Conclusions

Based on the results obtained from the study, the following conclusions are drawn;

1) Adding high FA quantity improved the plastic properties of concrete, providing better workability and consistence.
2) The compressive strength results show that the concrete can gain acceptable compressive strength even if the cement content is less than of FA, as seen in the 50% and 60% FA mixes.
3) HVFA concrete mixtures can result in equally or more durable and less permeable concrete as the standard 30% FA concrete which is good for concrete structures that are constantly exposed to moisture.
4) The shrinkage testing showed that HVFA concrete mixtures got slightly higher shrinkage that the 30% FA concrete.
5) The substitution of cement with higher FA content can reduce the costs of concrete in terms of binder materials by up to 50%, as the FA is relatively cheaper than the cement.

V. Acknowledgment

I would like to acknowledge the assistance from the staff of Contest laboratory and their input regarding testing concrete for durability and shrinkage. I would also like to acknowledge the input of Mr E. Makhathini from Durban University of Technology with regard to preparation and making of tests specimen. The guidance provided by the Supervisor, Professor D. Allopi from DUT enabled this paper to be successful.

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