# COMPRESSIVE STRENGTH OF A CONCRETE MIX FOR PAVEMENT BLOCKS INCORPORATING INDUSTRIAL BY-PRODUCT

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**ABSTRACT**

Concrete block paving for roads has been proposed as part of a concept on sustainable infrastructure. In an effort to respond to sustainability and environmental awareness, the use of industrial by-products has been employed in the mix design of the concrete for a block paving system. This contributes towards preservation of natural resources as waste materials from industrial processes are used. Class F fly ash obtained from a coal power station in Vereeniging in South Africa was used for the study. Compressive strength tests were done on concrete cubes containing varying fly ash contents from 0% to 90% as replacement for cement by mass. A decrease in compressive strength and increase in workability was observed with increasing fly ash content. A decrease in water requirement while still producing a workable mix compared to the conventional concrete was also observed with an increase in fly ash content. This would also contribute to the ecological footprint by decreasing the water demand for mixing. The optimal mix from the initial laboratory experiments contained 50% fly ash and exhibited a compressive strength of 37.3 MPa at 28 days.

## 1 INTRODUCTION

A block paving system for application in low volume roads has been proposed to support the concept of sustainable road infrastructure. The conceptualised block paving system aims to address some current urban infrastructure challenges faced by the road construction industry as well as road users. These challenges include long closure periods during road constructions and maintenance, lack of flexible systems for utility provisions and poor drainage control. As part of the development of the block paving system, the incorporation of environmentally sustainable materials will be investigated.

Conventional construction materials traditionally use natural resources which can be damaging to the environment by causing resource depletion and the emission of greenhouse gases. Safiuddin et.al (2010) highlights that scarcity of raw materials and the high energy prices are now global concerns which can be alleviated through the use of alternative materials. According to Safiuddin et.al (2010) construction material costs are increasing due to high demand, thereby causing resource depletion and escalating energy prices.

Considering that majority of South Africa's electricity consumption is supported by coal-fired power stations, an excessive amount of coal combustion by-products are produced as a result. Fly ash is one of the by-products from the combustion process and is stored in the form of open stockpiles as a waste product. The incorporation of fly ash in the concrete mixture for the block paving is aimed at re-cycling industrial by-products for use in innovative road construction materials.

This paper details the laboratory investigation of optimising South African Class F fly ash content in a concrete mix to achieve a compressive strength requirement of 30MPa. Class F fly ash used in this investigation is considered as low in lime content compared to Class C fly ash according to ASTM C618 classifications. Deo (2014) reported that low lime fly ash is dependent on the lime content of cement for pozzolanic reactions to take place and therefore gain strength.

## 2 MATERIALS

The main objective was to produce for a concrete mix that can achieve a compressive strength of 30MPa as recommended by the Cement and Concrete Institute (2011) for concrete blocks. The following materials were used.

### 2.1 Fly Ash

The fly ash used was Class F fly ash from the coal-fired Lethabo power station in Vereeniging. Scanning Electron Microscope (SEM) images were taken of the fly ash sample and they show the spherical nature of the fly ash particles which also vary in size. This can be seen in Figure 1 below which shows the fly ash powder at a magnification of 200X. However, it can also be seen from Figure 2 that not all the particles are spherical and a few particles are more angular in shape. Figure 3 and Figure 4 show that the fly ash particles are composed of rod-like structures and smaller globular units.

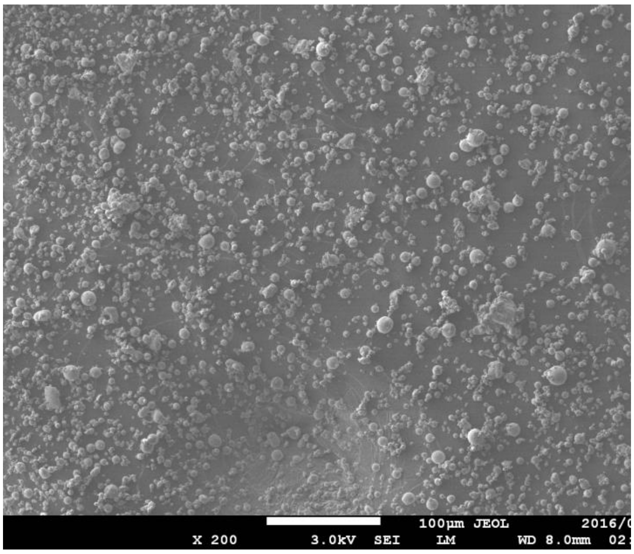



**Figure 1: Fly Ash at 200X Magnification**

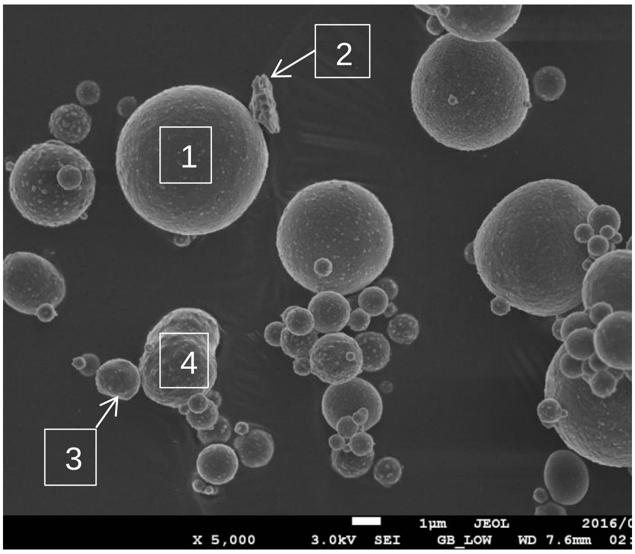



**Figure 2: Fly Ash at 5 000X Magnification**

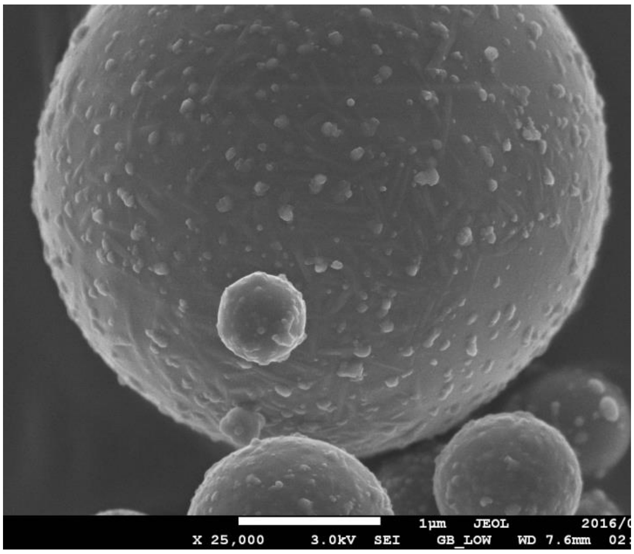



**Figure 3: Fly Ash at 25 000X Magnification**

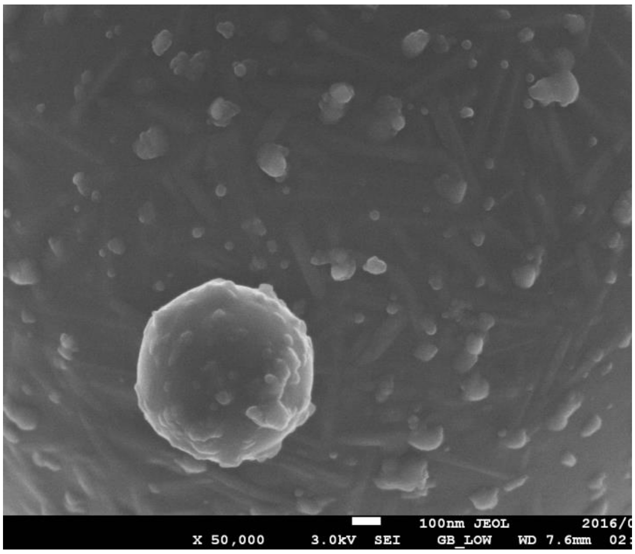
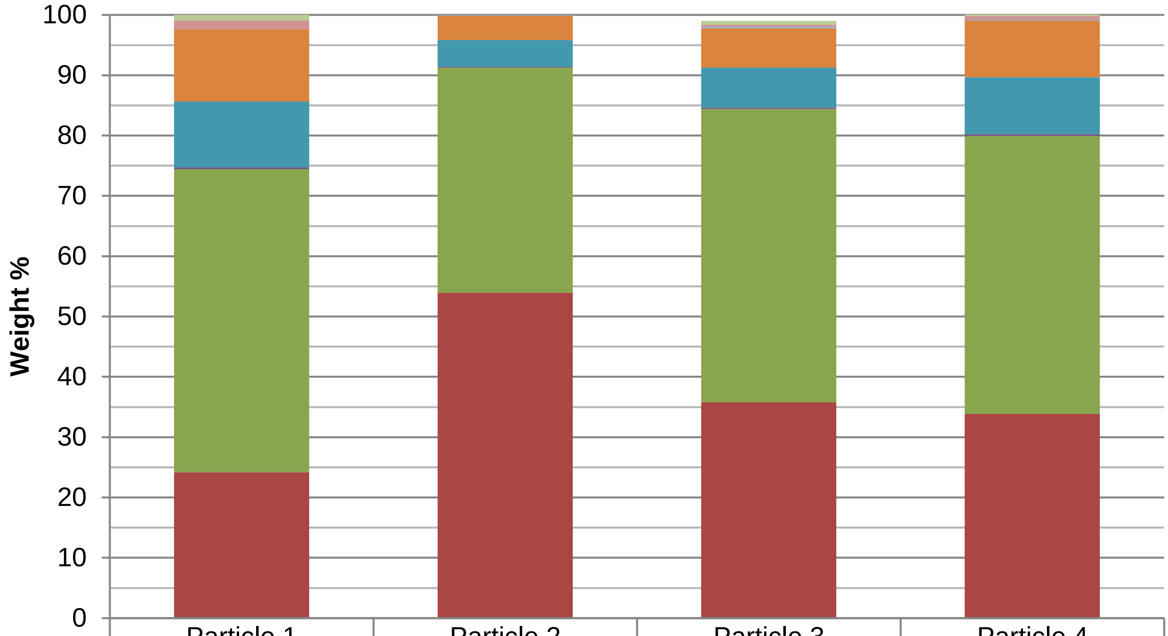



**Figure 4: Fly Ash at 50 000X Magnification**

An Energy Dispersive Spectroscopy (EDS) comparison was done on an angular particle and a spherical one (shown in Figure 2) in order to observe any compositional variations which could explain the differences in shape. Table 1 shows the EDS findings from the analysis done on particles 1 to 4 in Figure 2.

**Table 1: Elemental weight composition from EDS**




| | Particle 1 | Particle 2 | Particle 3 | Particle 4 |
|---|---|---|---|---|
| Fe | 0.96 | 0 | 0.64 | 0.65 |
| Ca | 1.47 | 0 | 0.33 | 0.58 |
| K | 0 | 0.13 | 0.25 | 0.2 |
| Si | 11.95 | 4.05 | 6.55 | 9.38 |
| Al | 10.86 | 4.41 | 6.55 | 9.38 |
| Mg | 0.35 | 0.13 | 0.26 | 0.33 |
| O | 50.2 | 37.35 | 48.67 | 46.1 |
| C | 24.22 | 53.93 | 35.76 | 33.85 |

The particles are primarily composed of Carbon and Oxygen, fewer amounts of Aluminium and Silicon and trace amounts of Magnesium, Potassium, Calcium and Iron. Deo (2014) attributes the strength development in concrete containing fly ash to the silica and alumina in the fly ash. The high Carbon readings in the sample is most likely unburnt Carbon from the coal burning process and the high Oxygen content can be attributed to the fact that the other elements exist as oxides in the fly ash (See Table 2). Table 2 is the composition of the ash as received from the manufacturer.

**Table 2: Composition of fly ash product (Mgangira, 2015)**

| Parameter | Range of Composition (%) |
|---|---|
| $SiO_2$ | 51.0 – 65.0 |
| $Al_2O_3$ | 25.0 – 35.0 |
| $Fe_2O_3$ | 3.0 – 5.0 |
| CaO | 1.0 – 6.0 |
| MgO | 0.5 – 2.0 |
| Loss On Ignition (LOI) | 0.8 – 2.5 |

Particle 2 does not contain Calcium and Iron compared to the other particles while Particle 1 does not contain Potassium. The low calcium content is indicative of a Class F fly ash which is low in lime (Cao).

Particle 2, which is the most angular in shape, has a lower weight composition of Silicon and Aluminium than the other particles and higher Carbon content by weight which may be attributed to its shape. Kutchko & Kim (2006) showed that unburned Carbon particles tended to be irregularly shaped and on the upper end of the size distribution. According to Sun et al (2001) angular particles can belong to the "irregular dense particle" sub-group of aluminosilicates in fly ash or the unburnt char group which has three sub-groups, all of which consist of angular particles.

### 2.2 Biological Activator

Given the low slumps observed and recorded (in Table 4), a biological activator was used in order to improve the workability of the concrete. The biological activator was added to the optimum concrete mix after initial mixes were tested for compressive strength. The optimum mix was selected based on meeting the minimum 28 day strength requirement as well as containing at least 50% fly ash replacement of cement by mass.

### 2.3 Cement

Pozzolanic cement of strength class 32,5N was used for all the mixes. This category of cement contains between 45 and 64% clinker, 36 to 55% fly ash as an additive and 0 to 5% minor additional constituents according to the South African National Standards (SANS 50197-1) classification. This would mean that even the reference mixes which have no additional fly ash as a separate ingredient will contain at least 36% fly ash due to the cement composition used in the experiment.

### 2.4 Aggregates

The coarse and fine aggregates used in the concrete mix were obtained from a quarry in Pretoria which supplies meta-quartzite rock. The selected stone size for the coarse aggregate was 13.2mm due to restricted space in the moulds for paver blocks. The grading analysis for the sand used is presented in Table 3.

## 3 METHOD

### 3.1 Mix Designs

The C&CI method based on the American Concrete Institute standard (ACI 211.1-91) was used for the various mix designs. Nine concrete mixes, with three different water:binder ratios (0.4, 0.3 and 0.2) and three different fly ash contents (0%, 50% and 90%) were initially selected for the laboratory investigation. Low water ratios were used because fly ash concrete has a lower water requirement for strength development compared to cement only concrete (Malhotra & Mehta, 2002). The fly ash contents are represented as percentage replacements of cement by mass.

**Table 3: Sand grading analysis**

| Sieve Size (mm) | Passing % |
|---|---|
| 53 | 100.0 |
| 37.5 | 100.0 |
| 26.5 | 100.0 |
| 19 | 100.0 |
| 13.2 | 100.0 |
| 9.5 | 100.0 |
| 6.7 | 100.0 |
| 4.75 | 98.8 |
| 2.36 | 68.8 |
| 1.18 | 46.5 |
| 0.6 | 32.5 |
| 0.425 | 27.7 |
| 0.3 | 27.9 |
| 0.15 | 20.7 |
| 0.075 | 17.3 |

The initial designs were subsequently adjusted after slump measurements were taken. It became evident after mixing the first batch of concrete from mix 1 that a slightly higher initial water content of 0.46 was required instead of a water content of 0.4 considering that workable reference mixes with even lower water contents would still need to be mixed. However it was also important not to take the water content too high since the fly ash concrete would require the lower water contents to achieve comparable strength. The adjusted mix designs which account for these considerations are shown in Table 4. Subsequently, the mixes which were tested had three different water:binder ratios of 0.46, 0.36 and 0.28.

**Table 4: Final mix proportions per m$^3$ for cube compressive strength tests**

| Batch | FA content (%) | w/b* | Cement (kg) | Fly ash (kg) | Stone (kg) | Sand (kg) | Water (litres) | Activator (litres) | Slump (mm) |
|---|---|---|---|---|---|---|---|---|---|
| Mix 1- reference 1 | 0 | 0.46 | 457 | 0 | 1062 | 660 | 210 | 0 | 10 |
| Mix 2 | 50 | 0.46 | 228 | 228 | 1062 | 586 | 210 | 0 | 100 |
| Mix 3 | 90 | 0.46 | 46 | 411 | 1062 | 526 | 210 | 0 | 130 |
| Mix 4 - reference 2 | 0 | 0.36 | 583 | 0 | 1062 | 546 | 210 | 0 | 0 |
| Mix 5 | 50 | 0.36 | 292 | 292 | 1062 | 451 | 210 | 0 | 10 |
| Mix 5A | 50 | 0.36 | 292 | 292 | 1062 | 451 | 210 | 2.87 | 15 |
| Mix 5B | 50 | 0.36 | 292 | 292 | 1062 | 451 | 210 | 5.74 | 20 |
| Mix 6 | 90 | 0.36 | 58 | 525 | 1062 | 546 | 210 | 0 | 35 |
| Mix 7 - reference 3 | 0 | 0.26 | 808 | 0 | 1062 | 344 | 210 | 0 | - |
| Mix 8 | 50 | 0.28 | 404 | 404 | 1062 | 212 | 226 | 0 | 0 |
| Mix 8A | 50 | 0.28 | 404 | 404 | 1062 | 212 | 226 | 3.10 | 5 |
| Mix 8B | 50 | 0.28 | 404 | 404 | 1062 | 212 | 226 | 6.21 | 10 |
| Mix 9 | 90 | 0.28 | 81 | 727 | 1062 | 106 | 226 | 0 | 55 |

*water:binder ratio where fly ash and cement is considered as the binder

The biological activator was added to Mix 5 and 8 to observe any improvements in consistency. The activator was added in proportion to the amount of binder in the respective concrete mix then doubled to observe the effects on increasing the biological activator content. Concrete mixes with the activator are labelled as 5A, 5B, 8A and 8B.

### 3.2 Specimen preparation

Concrete mixing was done in a laboratory pan mixer and in accordance with SANS 5861-1. Slump tests were performed on the mixes to measure consistency as described in SANS 5862-1 and recorded as per Table 4. Owens (2009) recommends the Vebe test for concrete mixes which have a slump of 10mm or less as the slump test “cannot differentiate between no-slump concretes of varying worakability”. Consistency measured using the Vebe test will be considered for low slump mixes obtained in on-going research.

The mixes were then prepared and cured according to SANS 5861-3. 150x150x150mm moulds were used for casting the concrete cubes. An exception to the curing method described in the standard was made for the 90% fly ash specimens due to the specimens disintegrating once placed in water. These specimens were therefore cured in heavy duty plastic bags; mixes 3, 6 and 9 were cured in the heavy duty bags before crushing on the appropriate days.

Three specimens were tested per mix and compacted on a vibrating table as per the national specification SANS 5861-3.

### 3.3 Compressive strength tests

Compressive strength tests were conducted according to SANS 5863. The cast concrete cubes were tested at 7, 14, 28 and 56 days. Each test batch was prepared for a specific age.

Compressive strength tests were done at 56 days because mixes containing fly ash were anticipated to have higher strengths at 56 days compared to their 28 day strengths. Previous researchers including Zhang et al (1997) and Mehta (2009) have shown that the strength of high volume fly ash concrete can surpass the strength of reference mixes containing no additional fly ash between 28 and 90 days. The fly ash used in these investigations was high calcium high sulphate fly ash.

## 4 DISCUSSION OF RESULTS

The target strength for the concrete was 30 MPa, the compressive strengths of the different mixes are shown in the figures below at 7, 14, 28 and 56 days.

Since the cement used for the experiment already contained between 36% and 55% of fly ash, the resultant fly ash content in the 50% fly ash mixes actually contained between 71% and 77.5% fly ash as replacement of cement by mass. The 90% fly ash mixes therefore contained between 93.6% and 95.5% fly ash. The low lime content of the fly ash used attributes to the the low compressive strengths achieved by these mixes.

The reference mixes without additional fly ash demonstrated the highest compressive strength values as expected with Mix 4 (w:b=0.36) exhibiting the highest compressive strength of 53.0MPa at 28 days. Although these mixes had the highest strengths, they also had the lowest workability as demonstrated by the respective low slump values in Table 4. Mix 7, which was the reference mix for a water:binder ratio of 0.28, could not be cast due its unworkable consistency and therefore not included in the results. Strength development in the reference mixes was also quicker than in the mixes with additional fly ash.

Figure 5 shows that at a water:binder ratio of 0.46, the 56-day strengths showed a significant increase from the respective 28-day strength values. The compressive strength increased by 71.6% and 93.5% for the 50% fly ash and 90% fly ash mixes respectively. This pronounced increase between 28-day strengths and 56-day strengths was not seen in the other fly ash mixes with lower water:binder ratios.

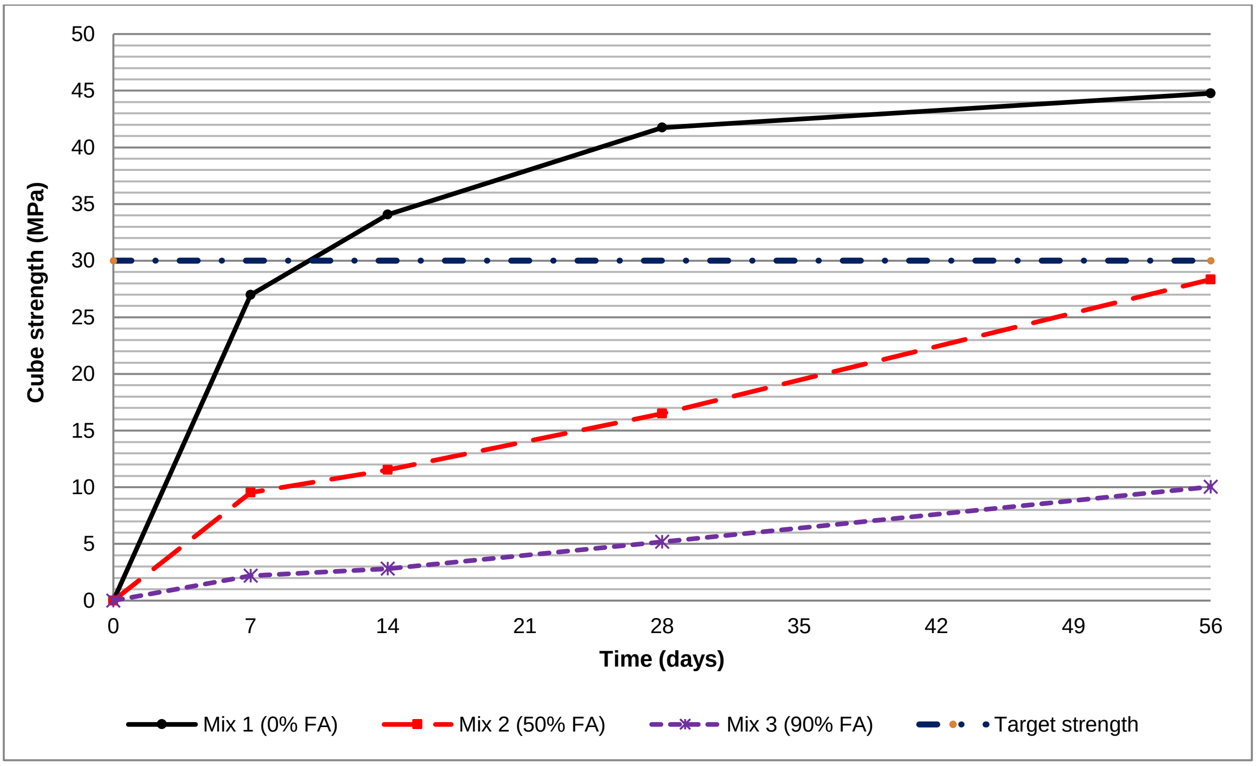



**Figure 5: Strength development for mixes 1, 2 and 3 with w:b = 0.46**

Unlike compressive strengths for a water:binder ratio of 0.46, the two lower water ratios (0.36 and 0.28) did not show significant improvement in 56-day strength compared to their respective 28-day strengths as seen in Figures 6 and 7. However, the strength development in all the mixes showed a consistent trend of faster strength gain with a decrease in fly ash content which can be seen in Figures 5 to 7.

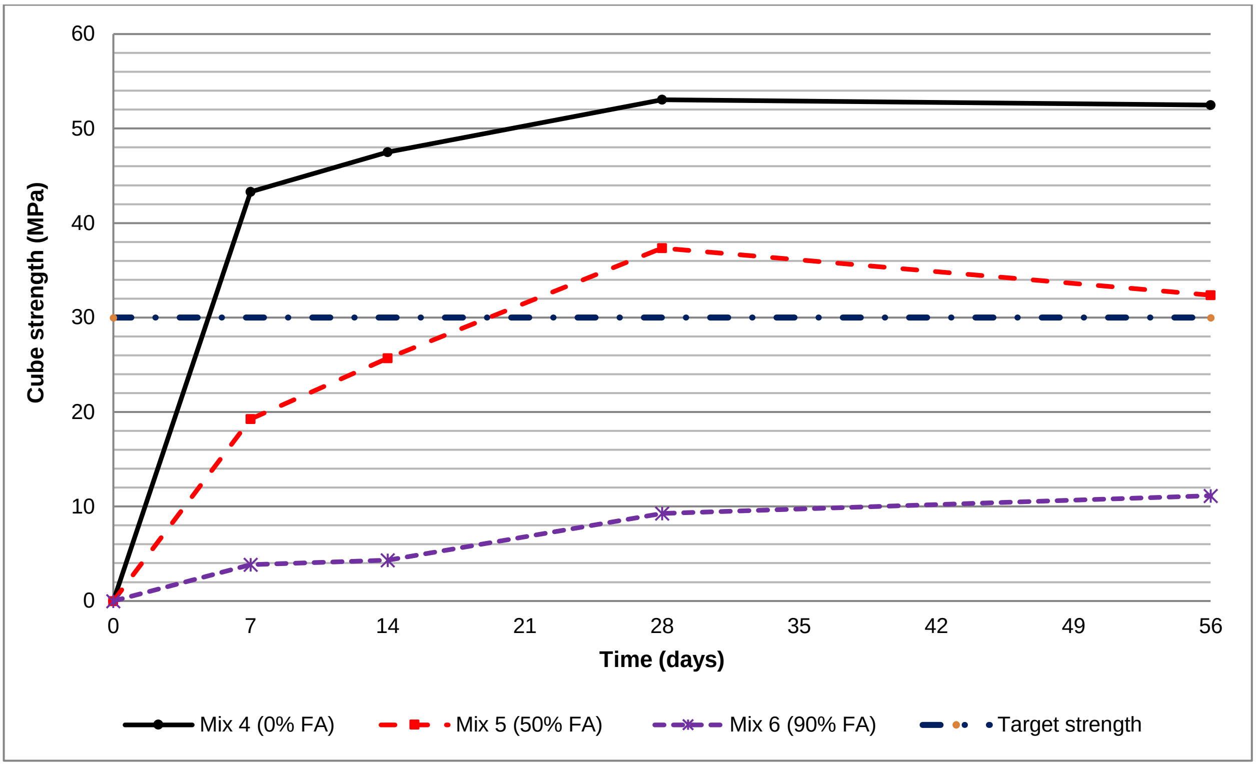



**Figure 6: Strength development for mixes 4, 5 and 6 with w:b = 0.36**

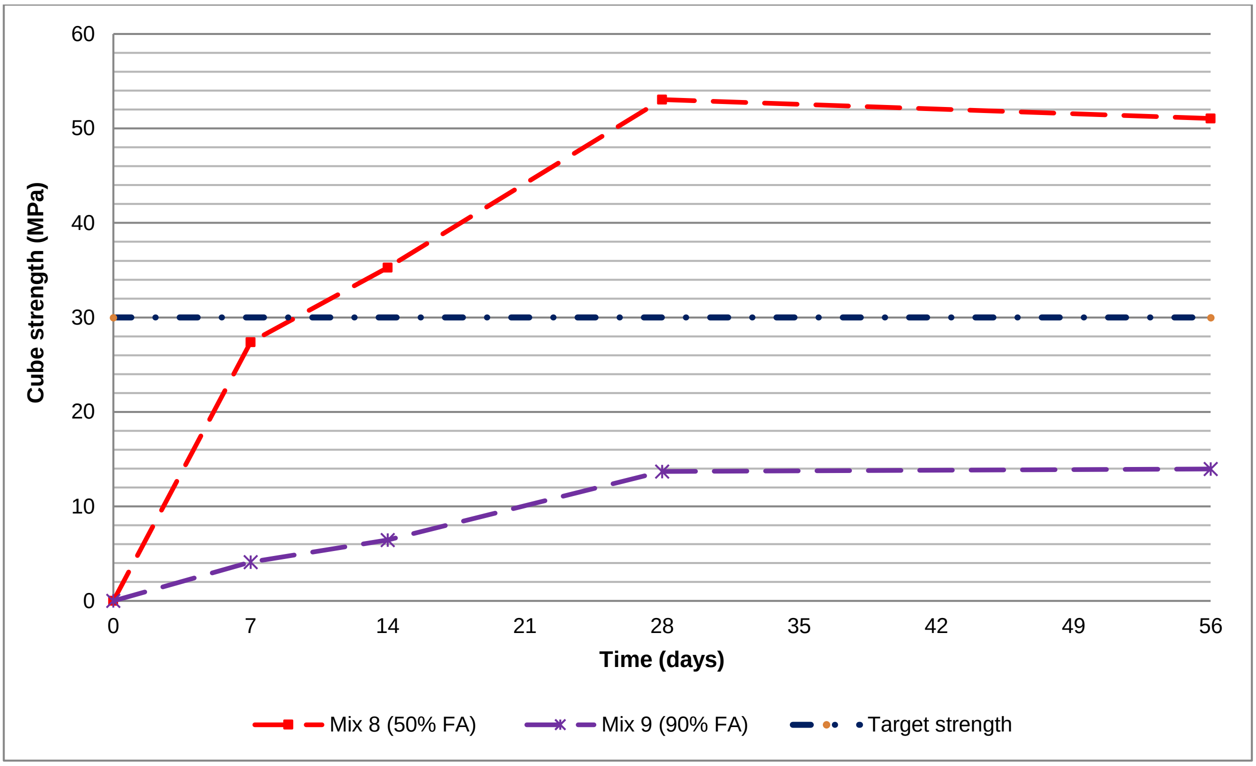



**Figure 7: Strength development for mixes 8 and 9 with w:b = 0.28**

As expected, the compressive strength increased with a decrease in water:binder ratio for a given fly ash content which can be observed in Figures 8 and 9.

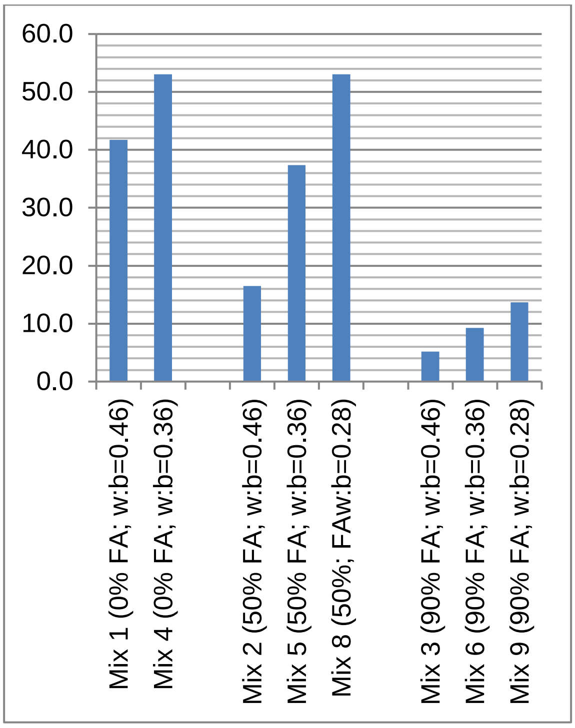



**Figure 8: Comparison of 28-day compressive strength, MPa**

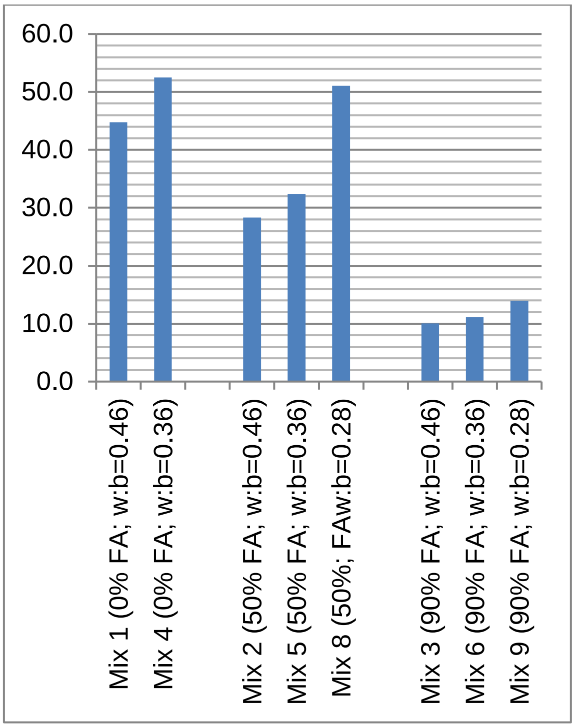



**Figure 9: Comparison of 56-day compressive strength, MPa**

A biological activator was added to Mix 5 and Mix 8 to assess the effect on workability. Mixes 5A and 5B contained 13.7cc and 27.3cc of activator per litre of water respectively. Mixes 8A and 8B contained 13.7cc and 27.5cc of activator per litre of water respectively. The mixes with biological activator added showed a slight increase in workability but an overall reduction in compressive strength. Slump values are shown in Figures 10 and 11 compared to the respective control mixes.

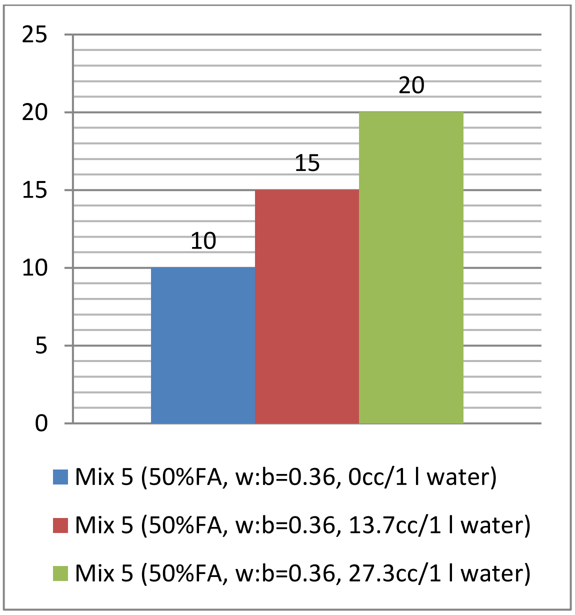



**Figure 10: Comparison of slump values (mm) with increasing activator content in mixes with w:b = 0.36**

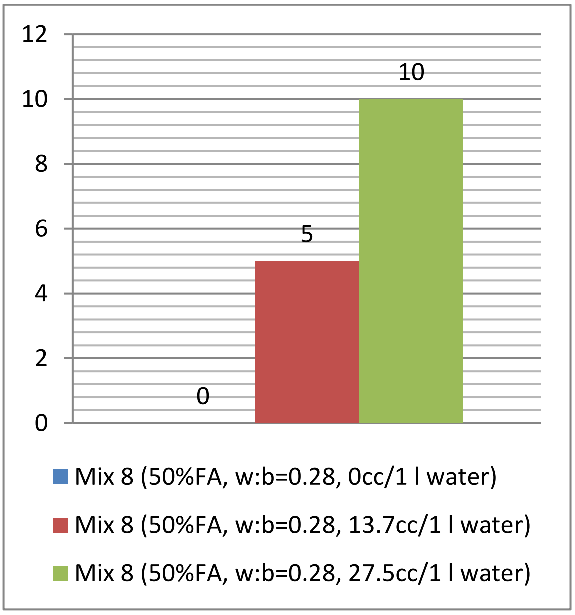



**Figure 11: Comparison of slump values (mm) with increasing activator content in mixes with w:b = 0.28**

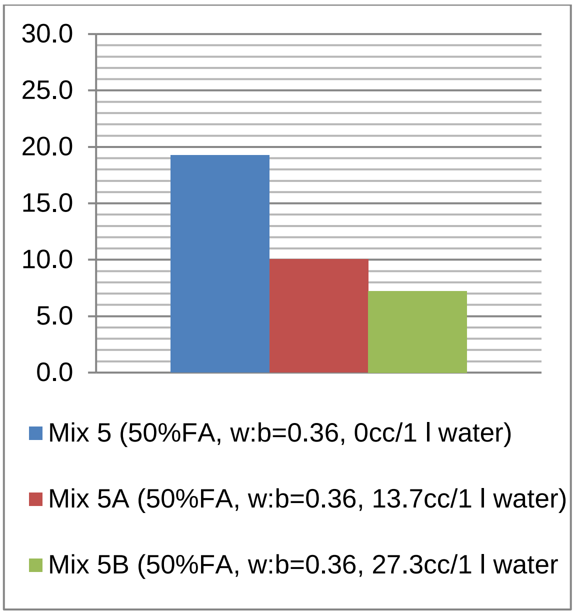



**Figure 12: Comparison of 7-day compressive strength (MPa) with increasing activator content at w:b =0.36**

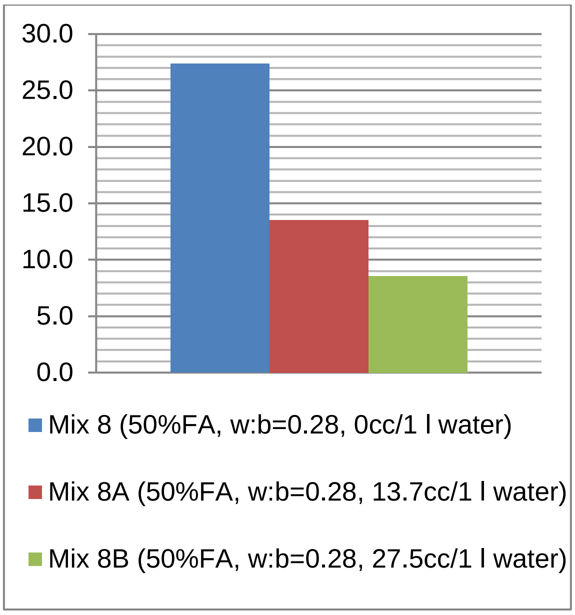



**Figure 13: Comparison of 7-day compressive strength (MPa) with increasing activator content at w:b =0.28**

Although, the addition of biological activator slightly improved workability, a reduction in compressive strength was also observed with an increase in activator(See Figures 12 and 13).. The addition of 13.7cc biological activator per litre of water reduced the compressive strength by 47.8% and 62.4% for Mix 5A and 8A respectively. The compressive strength was reduced by 62.4% and 68.8% for Mix 5B and 8B respectively

It is also worth mentioning that the concrete texture and colour changed by increasing the fly ash content. The colour became lighter as the fly ash content increased. The high volume fly ash specimens also had a smoother finish and were more sandy textured compared to the reference mixes. It would therefore be recommended to use the high volume fly ash concrete with a protective surface layer for pavement applications.

## 5 CONCLUSION

The aim of this laboratory investigation was to produce a concrete mix with the highest possible amount of fly ash which also met the strength requirement of 30 MPa for concrete paving blocks. The high volume fly ash concrete would serve as a more environmentally sustainable solution to conventional concrete. From the above investigation it can be seen that in order to produce a fly ash concrete mix which achieves the required strength, it is recommended that Mix 5 from this investigation be used. Mix 5 achieved a compressive strength of 37.3MPa at 28 days and contains additional fly ash content of 50% fly ash resulting in a concrete mix with total fly ash content between 71% and 77.5%. This was achieved using a water:binder ratio of 0.36.

From the investigation it can also be seen that:

- The strength development over time is slower with increasing fly ash content.
- 7, 14, 28 and 56 day-strength of the concrete is reduced by increasing the fly ash content.
- Workability improved with the addition of fly ash.
- The addition of biological activator improved workability of concrete.

Future research will include assessment of the durability of the selected mix with particular reference to concrete block paving and incorporating other “by-products materials” into the concrete mix in order to produce a functional concrete paving block system in support of the principle of sustainably-oriented road infrastructure development.

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