Sustainable Partial Cement and Water Replacement in Concrete Using PFA and Super Plasticiser.

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Abstract
Cement is an important material used in the production of many concrete based building elements. Despite its importance, the production costs and unit price are high. Cement is also a potential hazardous material. This experimental study considered the effect of partially replacing cement content in concrete by 30% with Pulverised Fuel Ash (PFA) referred to as fly ash. The study further considered the effect of introducing 4% Superplasticiser (SP) to the OPC based concrete. Three different mix designs where formulated. The first one was based on Ordinary Portland Cement (OPC) as a control mix; the second mix was based on Ordinary Portland Cement mixed with PFA while the third one had Ordinary Portland Cement and Superplasticiser (SP). Results indicated that introducing 30% PFA to the OPC based mix reduced the concrete compressive strength at 28 days by an average of 27% for low water cement ration concrete. Adding superplasticiser to the OPC based concrete reduced the concrete compressive strength by 7%. The study concluded that replacing up to 30% of cement in concrete with PFA could reduce concrete production costs on a project while retaining the acceptable levels of concrete strength, density and workability. Adding superplasticiser showed that the water content can be significantly reduced with minimal effect on concrete strength and density. The superplasticiser showed significant effect on the concrete workability.

Keywords: Cement replacement, Fly ash, Superplasticiser, concrete compressive strength

1.0. Introduction

Partial cement replacement in concrete has become a popular practice and area of study with fly ash being one of the most common replacement materials. The study area of cement replacement in order to make concrete greener extends its studies to associated areas such as concrete workability, compressive strength and density.

2.0. Aim

The aim of this study was to experimentally investigate the feasibility of partially replacing cement in concrete by up to 30% with Pulverised Fuel Ash (PFA). Further, the study considered the effect of adding 4% Superplasticiser (SP) to the OPC based concrete without significantly compromising the original strength and properties of the original OPC based mix design. The mixes were based on specially developed mix designs.

3.0. Objectives

In order to achieve the above aim, the following objectives were drawn:

3.1. To design two concrete mixes 0.3 and 0.5 water cement ratios that would be used in the laboratory experiments
3.2. To prepare and design three different mixes for mix design as follows: OPC only, OPC/PFA and OPC/Superplasticiser.
3.3. To conduct density, workability and compressive strength tests using the OPC only mix as a benchmark.
3.4. To establish the independent effect of PFA and super plasticiser on the density, workability and compressive strength of designed concrete in the study.

4.0. Study Justification

While many studies in this field as seen in the literature review have replaced cement with up to 20% PFA levels, this study extended the cement replacement to 30%. This was achieved through deployment of different mix designs.

The benefits of the study include cement replacement limits and justification for extending the cement replacement concept up to 30% without significant loss of compressive strength and density, which eventually reduces energy consumption during concrete production and environmental damage. This would further promote the utilisation of PFA from a coal waste material to a useful raw material in the production of concrete. The study further demonstrated the feasibility of significantly reducing water content without affecting the intended mix design even in terms of strength, density and workability of the concrete.

5.0. Risk Assessment

While PFA is a one of the good and ultimate cement replacement material, it has the potential to contain other mineral deposits such as aluminium and lead which could negatively affect the quality of the concrete. The study proposed that the PFA must be subjected to chemical and composition laboratory analysis before it is declared suitable for use as cement replacement material. With PFA being extracted from different sources of coal mines its samples must be subjected to consistent analysis and testing for presence of other minerals which could adversely affect the concrete.

6.0. Literature review

According to Zachar and Naik (2010), the use of fly ash in concrete has been widely shown to be an effective way to minimise the cost of the concrete by means of partial cement replacement. Using fly ash as a cement replacement reduces the proportional amounts of Green House Gas (GHG) production and other environmental effects of cement production. The use of fly ash as cement replacement material also improves the performance of concrete that is made with other recycled by-products, Zachar and Naik (2010).

Thomas (2007) experimental results revealed that fly ash is used as a Supplementary Cementitious Material (SCM) in the production of Portland cement concrete. A supplementary cementitious material, when used in conjunction with Portland cement, contributes to the properties of the hardened concrete through hydraulic or pozzolanic activity, or both. Below is table 1 showing dosage ranges of fly ash.

Level of Fly Ash **% by mass of total cementitious material**	Classification
<15	Low
15 - 30	Moderate
30 - 50	High
>50	Very High

Table 1: Dosage Levels of Fly Ash, Thomas, (2007)

Thomas (2007) further states that fly ash is a by-product of burning pulverized coal in an electrical generating station. Specifically, it is the unburned residue that is carried away from the burning zone in the boiler by the flue gases and then collected by either mechanical or electrostatic separators.

Meland (1983) states that hydration of cement is an exothermic reaction. High amount of heat is generally developed during this reaction. The generated heat causes the rise in temperature and accelerates the setting time and strength gain of mortar. In many structures, the rapid heat gain of cement increases the chances of thermal cracking, leading to reduce concrete strength and durability. The applications of replacing cement by high percentage of fly ash can reduce the damaging effects of thermal cracking. The cumulative heat of hydration evolved from paste containing fly ash remains less than that of ordinary Portland cement paste.

Alsadey (2012) concluded from his experiments that the workability of concrete can be increased by addition of superplasticiser. However, very high dosages of superplasticiser tend to impair the cohesiveness of concrete. Compressive strength is improved by superplasticiser compared with the control mix; On the other hand, even its ultimate strength is higher than the desired characteristic strength. Over dosage of superplasticiser were found to deteriorate the properties of concrete with indication of lower compressive strength. The study further established that if the dosage levels are lower than the optimum dosage, increase in admixture dosage might help to enhance the concrete characteristics.

Kubey and Kumar (2012) concluded that addition of superplasticiser beyond 2% increases compressive strength however this decreases with the increase of dosages of SP. With incorporation of SP up to 4%, there was significant increase of compressive strength of concrete mix with increase of age. When SP was added beyond 4% and up to 8% there was but a marginal increase in compressive strength at all ages. Beyond 8% and up to 10% the increase in compressive strength with aging was further reduced.

Dumne (2014) established that addition of superplasticiser along with 10% fly ash of cement content accelerates the compressive strength of self-compacting concrete and establishes the uniform and homogenous mix. This further gave marginal reduction in weight of hardened mix of concrete. The results showed that for the constant water cement ratio, increase of superplasticiser dose in Self-Compacting Concrete leads to gain of good self-compaction ability in addition to marginal reduction in unit weight. Moreover, there is also slightly increase in compressive strength than that of normal concrete mix.

Tamrakar and Mishra (2013) study revealed that the workability of concrete could be increased by addition of superplasticiser. However, very high dosages of SP tend to impair the cohesiveness of concrete. Slump loss can be reduced by using the chemical admixtures. However, effectiveness is higher for super plasticised concrete

Wankhede and Fulari (2014) states that concrete with 10% and 20% replacement of cement with fly ash shows good compressive strength for 28 days than normal concrete for 0.35 w/c ratio but in the case of 30% replacement of cement with fly ash ultimate compressive strength of concrete decreases. This is one of the main study objectives why this current study focused on improving the reduced strength of the 30% fly ash in the concrete by considering different mixes of concrete that could retain original properties of concrete despite replacing cement with 30% fly ash.

Balakrishna and Nataraja (2013) observed that cement is the most costly and energy intensive component of concrete. The unit cost of concrete can be reduced as much as possible by partial replacement of cement with Fly ash. The disposal of Fly ash is one of the significant issues for environmentalists because dumping of fly ash as waste material causes severe environmental problems. Other benefits of partial replacement of concrete with fly ash include lower water demand for similar workability, reduced bleeding and lower generation of heat.

Jatale et al (2013) states that in the view of global warming, efforts were being made to reduce the emission of CO2 to the environment. Cement Industry is major in contributor in the emission of CO2 as well as using up high levels of energy resources in the production of cement. By replacing cement with a material of pozzolanic characteristic, such as fly ash, the cement and the concrete industry together can meet the growing demand in the construction industry as well as help in reducing the environmental pollution. As the fly ash content increases there is reduction in the strength of concrete. This reduction is more at earlier ages as compared to later ages. This is expected, as the secondary hydration due to pozzolanic action is slower at initial stage for fly ash concrete. Density and air content of concrete mix are generally unaffected with the use of fly ash. Use of fly ash improves the workability of concrete. This phenomenon can be used either the unit water content of mix or to reduce the admixture dosage.

Islam and Islam (2010) experimental results showed that the optimum fly ash content was observed to be 40% of cement with 14% higher compressive strength than OPC mortar after 90 days curing. The corresponding increase in tensile strength was reported to be around 8%. The aim of this current study was to investigate if acceptable compressive strength levels could be attained without waiting for longer curing periods as stated in Islam and Islam (2010).

7.0. The experiment

The experiment was carried out at the Anglia Ruskin University Civil Engineering workshop located at the Business Innovation Centre for Medical and Advanced Engineering in Chelmsford, England. Two concrete mixes of water cement ratio 0.3 and 0.5 were designed. For each mix the workability test was carried out using the slump test (Figure 1) and the compaction factor method test (Figure 2). This was done to specifically establish the effect of PFA and superplasticiser on concrete workability. The concrete cubes cast were allowed to cure for 28 days in a curing tank (Figure 3) fitted with thermostat heater in order to maintain the constant temperature of the water. The aim of the experiment was to establish the strength of the concrete after the concrete maturity date and not the rate of concrete strength gain hence cubes being only tested at 28 days. Density tests (Figure 4) were also carried out using the buoyancy principle to measure the effects of PFA and superplasticiser on the concrete density. Lastly compressive strength tests were carried out by crushing the fully cured concrete cubes at 28 days using the compressive strength test machine as shown in figures 5a and 5b. The concrete cubes were labelled appropriately to distinguish them from each other as a quality control mechanism as shown in figure 6.

Figure 1 Slump test

Figure 2: Compaction factor test

Figure 3: Curing tank

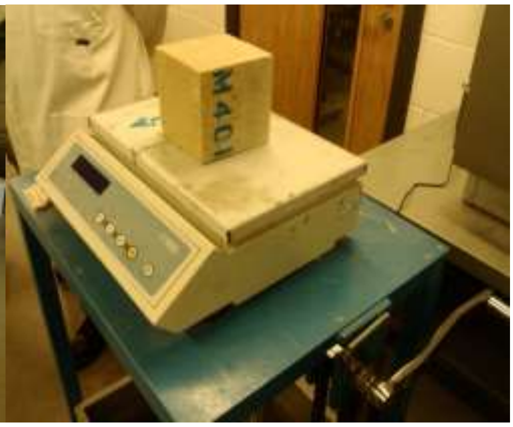


Figure 4: Density tests

Figure 5a: Concrete cube during testing

Figure 5b: Concrete cube after testing

Figure 6: Labelling of concrete cubes for quality control

Figure 7: Proceq pulse velocity machine test in use

8.0. Results verification

The compressive strength results were verified using the Proceq pulse velocity machine (Figure 7) in order to generate a second line of comparative non-destructive based test results. The tests were carried out before crushing the concrete cubes. The compressive strength values for the non-destructive testing were obtained from the machine readings and from the calculations based on the velocity of ultra sound from the remitter to the receiver. The velocity results were subjected to the velocity/concrete strength converter chart found in table 2 to determine the quality strength level of the concrete. The results for these tests are presented in figures 10 and 11.

Pulse Velocity **Km/s**	Concrete Quality (Grading)
Above 4.5	Excellent
3.5 to 4.5	Good
3.0 to 3.5	Medium
Below 3.0	Doubtful

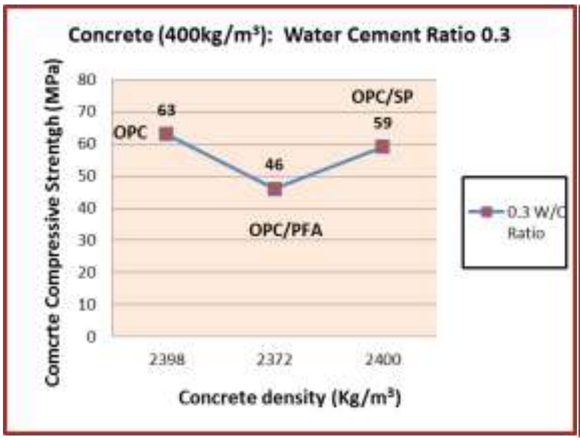
Table 2: Pulse velocity to concrete conversion table, (The concrete portal)

9.0. Results and discussion

9.1. Compressive strength and density

Figure 8 shows the effect of PFA and superplasticiser on the OPC concrete strength of 0.3 water cement ratio and cement content of $400kg/m^3$. This was a low water content concrete tested at 28days. This OPC mix gave a compressive strength of 63MPa at 28 days. By replacing the cement with 30% PFA, the compressive strength at 28 days was reduced to 46MPa. The pattern of the compressive strength is similar to that of density as seen in figure 8 except for the mix with superplasticiser which had the highest density of $2400kg/m^3$ due to the self-compacting nature of the additive. This density exceeded the $2398kg/m^3$ for OPC. The results strongly suggest that 30% of cement can be replaced with PFA and superplasticiser without significantly affecting the compressive strength of the concrete. The reduction of the compressive strength triggered by the introduction of PFA was still acceptable considering that most concrete structures require up to 35MPa strength. However the addition of 4% superplasticiser reduced the compressive strength from 63MPa to 59MPa but with a higher slump indicating that the water content could be significantly reduced for the same workability. This reduction amounted to 7%.

Figure 9 shows a repeat of figure 8 but with a water cement ratio of 0.5 and cement content of 270kg/m^3. The OPC compressive strength was 39MPa at 28 days. This concrete mix represented a lower cement content and higher water content mix.



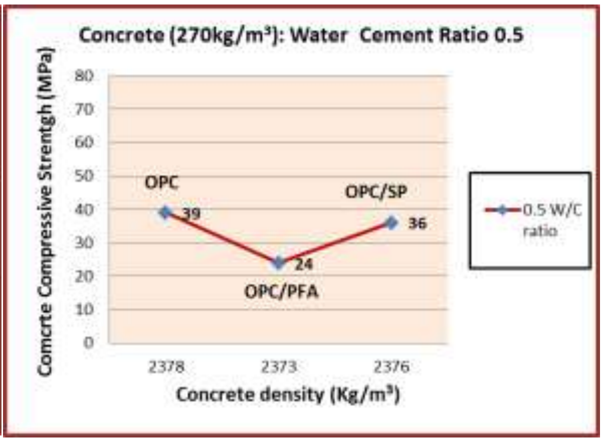
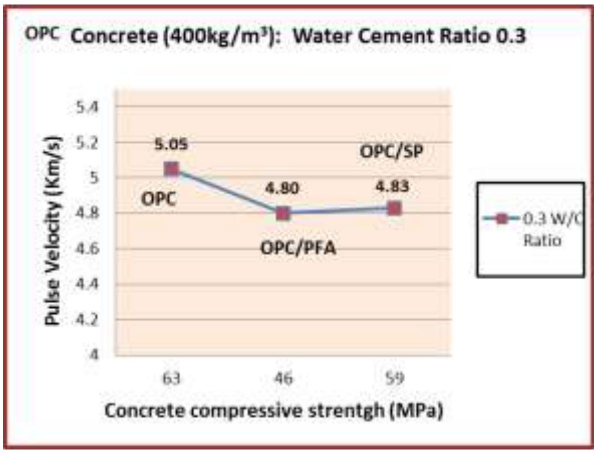


Figure 8: Compressive strength and density 0.3 W/C

Figure 9: Compressive strength and density 0.5 W/C



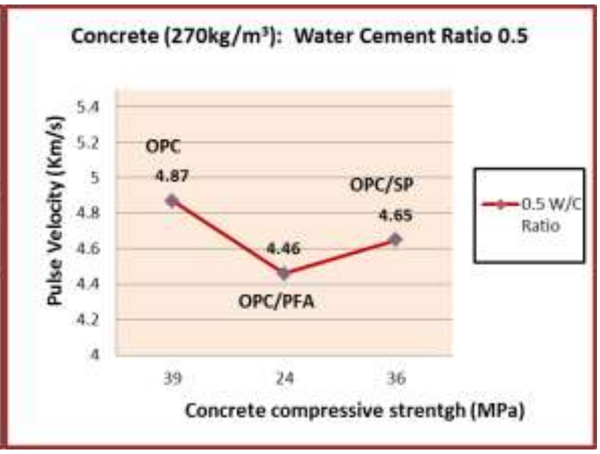
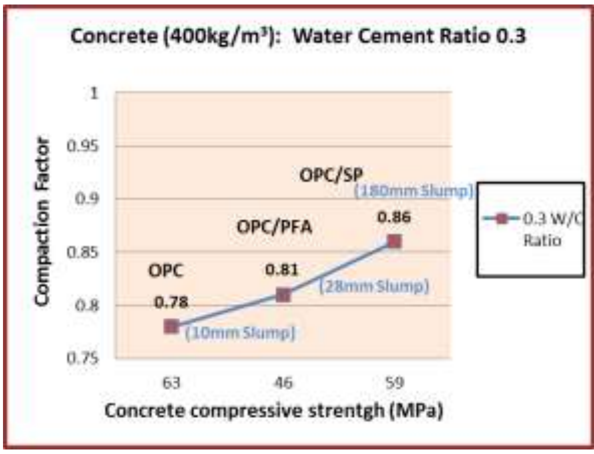


Figure 10: Pulse velocity and compressive strength WC 0.3

Figure 11: Pulse velocity and compressive strength WC 0.5



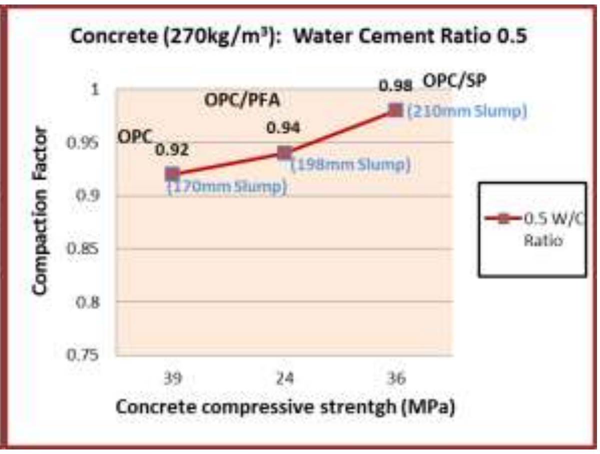


Figure 12: OPC/PFA/SP and concrete workability WC 0.3

Figure 13: OPC/PFA/SP and concrete workability WC 0.5

The replacement of 30% concrete with PFA reduced the compressive strength to from 39MPa to 24MPa at 28 days. The replacement of 30% cement with 30% PFA provided in high water content concrete provided much lower concrete grade results. This means that PFA would not be suitable in high water content mixture of 0.5 WC ratio in this case. PFA based concrete would require reduced water content in order to meet the mix design specifications. The addition of the superplasticiser to the OPC based mix reduced the compressive strength from 39MPa to 36MPa. Again the addition of superplasticiser had less significance on the compressive strength for the high water content concrete. Addition of superplasticiser to the OPC mix reduced the density from 2378kg/m^3 to 2376kg/m^3 for the PFA based. However the density for the OPC mixed with SP was higher than the one with OPC/PFA/ mix. The results based on OPC/SP were very close to the original OPC only results as seen in figures 8 and 9 but not for PFA.

9.2. Pulse velocity and compressive strength

In order to verify the results in figures 8 and 9, further experiments were carried out to establish the pulse velocities of the samples against compressive strength and density. This was useful in establishing the pattern of the results and the graphs. The pattern of results from the pulse velocity machine was similar and consistent with those of figures 8 and 9.

Figure 10 shows that the 400kg/m^3 concrete mix based on 0.3 water cement ratio produced the pulse velocities results as follows: OPC only: 5.05km/s, OPC/PFA: 4.80km/s and OPC/SP 4.83km/s. These results corresponded with 63MPa, 46MPa and 59MPa respectively as tabulated in figures 8 and 9. The higher the pulse velocity, the less the resistance and the better the strength and quality of the concrete. Table 2 indicates the conversion factors for pulse velocity to the quality of concrete compressive strength. The results from the Proceq pulse velocity machine were consistent with those obtained from the compressive strength machine. Figure 11 shows that the 270kg/m^3 cement content and 0.5 water cement ratio mix produced 4.87km/s for OPC, 4.46km/s for OPC/PFA and 4.65km/s for OPC/SP. The results showed consistency of the additives with the results from the compressive strength test. This pattern was also similar to that of figure 10 except for the difference in the values. These results indicated consistency of the concrete behaviour despite the difference in the mixes.

Despite the pulse velocity results being lower in the 0.5 water cement ratio (Figure 11) as expected, the pattern of results is consistent with those of figure 9 in relation to the compressive strength and in figure 11 in terms of pulse velocity. Results in figure 9 were justified by those in figure 11. The results show that cement can be confidently replaced with 30% PFA without adversely affecting the design of the concrete properties. This is applicable to low water and high cement content concrete. Superplasticiser on the other hand could be added to both higher and lower cement ratios while retaining the original strength of OPC only based concrete.

Lastly concrete mixes with superplasticiser would require having very low water content which saves water costs associated with the concrete.

9.3. OPC/PFA/SP and concrete workability

Figures 12 and 13 shows that addition of PFA to the OPC only based concrete increased the workability of the concrete. The addition of superplasticiser to the OPC only based concrete increased the concrete workability further despite its self-compacting effect that led to consistent concrete strength and density. The increase in workability was seen in both the slump test and compaction factor (CF) tests for the 0.3 and 0.5 water cement ratios. In the water cement ratio of 0.3, the OPC mix had 10mm slump and 0.78 CF. Introducing the PFA increased the workability to 28mm slump and 0.81CF. Addition of superplasticiser to the OPC only based mix increased the workability to 180mm and 0.86 CF. In the water cement ratio of 0.5, the OPC mix had 170mm slump and 0.92 CF. Introducing the PFA increased the workability to 182 slump and 0.96 CF. Addition of superplasticiser to the mix increased the workability to 210mm and 0.98 CF.

10. Conclusion

The results from this series of experiments indicate that the replacing of 30% cement in concrete produces the following results:

1. Replacing 30% cement with PFA reduced the strength of the concrete by 27% from 63MPa to 46MPa. This is still acceptable for most concrete specifications ranges from 25MPa to 35MPA. This was also reflected in the reduction of concrete density and increase in workability. This was further applicable to both low and high water/cement content which were 270Kg/m^3 and 400Kg/m^3 respectively.

2. Introducing superplasticiser to the OPC only concrete reduced the compressive strength by 7% from 63MPa to 59MPa for the 0.3 W/C ratio.
3. Introducing superplasticiser to the OPC only concrete mix for 0.5 W/C ratio only reduced the compressive strength from 39MPa to 36MPa.
4. The above results imply that superplasticiser could be used in low and high workability concrete.
5. The use of PFA and SP could significantly bring down the concrete and cost and the cost of environmental damage. The PFA must however be subjected chemical analysis to ensure that there are no heavy metals and impurities that may compromise the strength of the concrete. The study did not consider other tests such as permeability because of the boundaries stipulated by the study. In addition the cumulative strength was not considered because the main aim of the experiments was in the final compressive strength of the concrete rather than the cumulative one.
6. The pulse velocity test was used to validate the concrete compressive strength values of the concrete mixes produced. The compressive strength results from the non-destructive testing machine were consistent with those for the destructive testing compressive strength machine
7. The study did not take into account the concrete strength and density of the mix design before and beyond the mature curing period of 28 days.
8. The study proposes a further set of experiments that would use fly ash in combination with superplasticiser using 0.3 and 0.5 W/C ratios in order to assess the feasibility of combining both additives while retaining

the maximum compressive strength, appropriate workability and maximum density.

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