MODELING THE EFFICIENCY FACTOR OF FLY ASH IN CONCRETE

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ABSTRACT

The use of fly ash (FA) as a supplementary cementitious material (SCM) with ordinary Portland cement (OPC) has many benefits and improves concrete performance in both the fresh and hardened state which are yet to be fully exploited in the New Zealand market. FA use in concrete greatly improves the workability in the plastic state (due in part to its unique spherical particle shape), decreased water demand and reduced heat of hydration. The density, strength, permeability and durability of hardened concrete also see improvements over standard concrete at fixed workability owing in part to a lower water/binder ratio. This paper will attempt to show a quantitative understanding of the efficiency of proportioning FA in concrete which is essential for its effective utilization, using a strength model.

INTRODUCTION

FA is a by-product from burning pulverized coal in electric power generating plants. During combustion, mineral impurities in the coal (clay, feldspar, quartz, and shale) fuse in suspension and float out of the combustion chamber with the exhaust gases. As the fused material rises, it cools and solidifies into spherical glassy particles called FA. FA is collected from the exhaust gases by electrostatic precipitators or bag filters. The fine powder does resemble OPC but it is chemically different. FA chemically reacts with the by-product calcium hydroxide released by the chemical reaction between OPC and water to form additional cementitious products that improve many desirable properties of concrete. All FA exhibit cementitious properties to varying degrees depending on the chemical and physical properties of both the FA and OPC. Compared to OPC and water, the chemical reaction between FA and calcium hydroxide typically is slower resulting in delayed hardening of the concrete.

Two types of FA are commonly used in concrete: Class C and Class F. Class C are often high-calcium FA with carbon content less than 2%; whereas, Class F are generally low-calcium FA with carbon contents less than 5%. In general, Class C ashes are produced from burning sub-bituminous or lignite coals and Class F ashes bituminous or anthracite coals. Performance properties between Class C and F ashes vary depending on the chemical and physical properties of the ash and how the ash interacts with OPC in the concrete. Many Class C ashes are self cementing, but not Class F ashes. Most, if not all, Class F ashes will only react with the by-products formed when OPC reacts with water.

The Benefits of Using FA. Concrete in its hardened state shows improved performance with:

- Greater strength. FA increases in strength over time, continuing to combine with free lime.
- Decreased permeability. Increased density and long-term pozzolanic action of FA, which ties up free lime, results in fewer bleed channels and decreases permeability.
Increased durability. The lower permeability of concrete with FA also helps keep aggressive compounds on the surface, where destructive action is lessened. FA concrete is also more resistant to attack by sulfate, mild acid, and soft (lime hungry) water.

Reduced alkali silica reactivity. FA combines with alkalis from OPC that might otherwise combine with silica from aggregates, thereby preventing destructive expansion.

Reduced heat of hydration. The pozzolanic reaction between FA and lime generates less heat, resulting in reduced thermal cracking when FA is used to replace a percentage of OPC.

Reduced efflorescence. FA chemically binds free lime and salts that can create efflorescence. The lower permeability of concrete with FA can help to hold efflorescence-producing compounds inside the concrete.

The ball-bearing effect of FA in concrete creates a lubricating action when concrete is in its plastic state. This means:

- Increased workability. Concrete is easier to place with less effort, responding better to vibration to fill forms more completely.
- Increased ease of pumping. Pumping requires less energy; longer pumping distances are possible.
- Improved finishing. Sharp, clear architectural definition is easier to achieve, with less worry about in-place integrity.
- Reduced bleeding. Fewer bleed channels decreases porosity and chemical attack. Bleed streaking is reduced for architectural finishes. Improved paste to aggregate contact results in enhanced bond strengths.
- Reduced segregation. Improved cohesiveness of FA concrete reduces segregation that can lead to rock pockets.
- Reduced slump loss. More dependable concrete allows for greater working time, especially in hot weather.

In order to determine the strength of FA concrete relative to OPC concrete at a required age, one of the methods of designing concrete mix is by using efficiency factor (k-value) concept.

There are no equivalent New Zealand or Australian standards regarding SCM efficiency factors but a number of international standards e.g. BS EN 206-1 use the application of k-value concept for FA conforming to BS EN 450-1 together with OPC type CEM I conforming to BS EN 197-1.

The maximum amount of FA to be taken into account for the k-value concept shall meet the requirement:

$$\frac{Fly\ Ash}{Cement} \leq 0.33 \ by \ mass$$  \hspace{1cm} \text{Equation 1}

If a greater amount of FA is used, the excess shall not be taken into account for the calculation:

$$\frac{w_F}{c_F + kF}$$  \hspace{1cm} \text{Equation 2}

Where: $w_F = \text{water content of concrete with FA (kg/m}^3)$$
$c_F = \text{cement content of concrete with FA (kg/m}^3)$$
$F = \text{FA (kg/m}^3)$$
$k = \text{efficiency factor}$
The following $k$-values are permitted for concrete containing CEM I:

- CEM I 32.5 \( k = 0.2 \)  
- CEM I 42.5 and higher \( k = 0.4 \)

The minimum OPC content required for relevant exposure class (BS EN 206-1 specifies 18 exposure classes) may be reduced by a maximum amount of $k \times (\text{minimum OPC content} - 200)$ kg/m$^3$ and the amount of (OPC + FA) shall not be less than the minimum OPC content required.

**EXPERIMENTAL**

All cementitious materials were supplied by Holcim New Zealand Ltd: Ultracem GP (MMC, Japan) and class F FA (Mundra, India). Typical chemical analysis of OPC and FA is shown in the ternary diagram in Figure 1; class F FA being high in silica content and low in CaO.

![Figure 1. Ternary diagram chemical composition.](image1)

Figure 2 shows the scanning electron microscope (SEM) micrograph and particle size distribution (PSD) of FA which shows the unique spherical particle shape of the FA. Both the class F FA and Ultracem GP have 50% PSD ~ 16 µm.

![Figure 2. Fly ash SEM micrograph and particle size distribution (PSD).](image2)
For the concrete mix designs normal graded materials, including fine, medium and coarse aggregates, were used as shown in Figure 3.

![Figure 3. Concrete mix design grading curve.](image)

The mixture proportions of the reference OPC concrete (without FA) are summarized in Table 1.

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Ratio</th>
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<tbody>
<tr>
<td>Water/Binder</td>
<td>0.52</td>
</tr>
<tr>
<td>Binder/Fine Aggregate</td>
<td>0.46</td>
</tr>
<tr>
<td>Binder/Coarse Aggregate</td>
<td>0.34</td>
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Potable water at ambient temperature was used. A common water reducing admixture was used at a content of 0.8% of the total cementitious materials (binder) in order to maintain the slump of the fresh concrete. The measured air content of the concrete mixtures was approximately 1.5%.

Class F FA was used at percentage levels 10, 25 and 35% for the purpose of this study by means of replacement and proportioning (see definitions below).

To evaluate the efficiency factor (k-value) of the FA, the water/binder level was adjusted such that compressive strengths at 28 days were equivalent to the reference concrete (without FA):

\[
w_0 = \frac{w_F}{c_F + kF} \quad \text{Equation 5}
\]

\[
k = \frac{w_F - c_F}{w_0 F} \quad \text{Equation 6}
\]

Where: \(w_0\) = water/binder ratio of reference concrete

A constant volume unit (1 m³) of concrete was chosen as a common comparison basis; when the FA was added to this unit, an equal volume proportion of fine aggregate was removed in order to maintain the yield.
The dry materials were mixed for 0.5 min. Then the water (with water reducing admixture) was added and the mixing was continued for a further 4.5 mins.

Fresh concrete tests were benchmarked against the relevant New Zealand standards and included: temperature, slump, slump loss (up to 60 minutes), bleed water, air content and density/yield. Specimens for semi-adiabatic calorimetry (Holcim MeToo-Heat) were moulded (80ø x 150 mm) and tested for set times and thermal profile. The specimens for strength measurements were cast in cylinders of 100ø x 200 mm, compaction via a vibration table and then covered to minimize water evaporation. Standard overnight curing was 21 °C. The moulds were stripped after 24 h and the specimens were moist cured (water bath) at 21 °C until testing.

Effects on concrete strength and fresh concrete properties due to batching temperature were conducted in the following way. Batching at 10, 21 and 30 °C followed by overnight curing at 21 °C then moist cured (water bath) at 21 °C until testing.

Effects on concrete strength due to seasonal curing temperature was conducted in the following way: Batching at 21 °C followed by overnight curing at 10 and 25 °C then moist cured (water bath) at 10 and 25 °C until testing.

The testing age was after 3, 7, 28 and 56 days. For each age, two specimens of each mixture were tested for compressive strength (and density) and the mean value of these measurements reported.

There are three basic approaches for selecting the quantity of FA in concrete:

- **Partial Replacement of OPC - simple replacement method**
  - In this method a part of the OPC is replaced by FA on a one to one basis by mass of OPC. In this process, the early strength of concrete is lower and higher strength is developed after 56-90 days. This method of FA use is adopted for mass concrete works where initial strength of concrete has less importance compared to the reduction of temperature rise.

- **Addition of FA as fine aggregates**
  - In this method, FA is added to the concrete without corresponding reduction in the quantity of OPC. This increases the effective cementitious content of the concrete and exhibits increased strength at all ages of the concrete mass. This method is useful when there is a minimum OPC content criteria due to some design consideration.

- **Partial replacement of OPC, fine aggregate, and water i.e. proportioning**
  - This method is useful to make strength of FA concrete equivalent to the strength of control mix (without FA) at early ages i.e. between 3 and 28 days. In this method FA is used by replacing part of OPC by mass along with adjustment in quantity of fine aggregates and water. The concrete mixes designed by this method will have a total weight of OPC and FA higher than the weight of the OPC used in comparable to control mix i.e. without FA. In this method the quantity of cementitious material (OPC + FA) is kept higher than quantity of OPC in control mix (without FA) to offset the reduction in early strength.
RESULTS AND DISCUSSION

FA: OPC Replacement, Fixed Water/Binder Ratio

The results of the concretes made at fixed water/binder ratio and replacement of OPC with FA are shown in Figure 4. As can be seen with increasing proportions of FA the workability (slump) and bleed water increases for a fixed water/binder ratio. The Holcim MeToo-Heat data shows reduced heat profiles with increasing amounts of FA and only marginally extended initial and final set times (<60 minutes) at all FA percentages. At all ages the compressive strengths of the FA blend concretes are lower than the reference OPC concrete.

Figure 4. Fixed water/binder ratio; concrete slump, bleed profile, Holcim-Heat and compressive strength as a function of fly ash.
FA: OPC Replacement, Fixed Workability (Slump)

The results of the concretes made at fixed workability (slump = 100 ± 10 mm) and replacement of OPC with FA are shown in Figure 5. As can be seen with increasing proportions of FA there can be afforded a reduction in water/binder ratio. As a consequence the bleed water profile show decreasing bleed compared to the reference OPC concrete especially in the 35% FA blend. The slump retention (slump vs time) is equivalent at all FA blend ratios under laboratory conditions. The compressive strengths of FA concretes at fixed workability are lower at early ages but show equivalence at 56 days (±2 MPa).

Figure 5. Fixed workability; water/binder ratio, bleed profile, concrete slump retention and compressive strength as a function of fly ash.
FA:OPC Proportioning with Efficiency Factor (k-value)

The results of the concretes proportioned with FA using the efficiency factor (k-value) are shown in Figure 6. As can be seen with increasing proportions of FA there can be afforded a reduction in OPC content (~90 kg/m³ at 35% FA for this mix design). However the compressive strengths of FA proportioned concretes are only marginally lower at early ages but show equivalence at 28 days (±2 MPa). Enhanced strengths are evidenced at 56 days.

![Less Cement per m³ than OPC Concrete vs Fly Ash Content](image1)

![Concrete Strength vs Fly Ash Content](image2)

![Concrete Strength Normalized to 28 Day](image3)

**Figure 6.** FA:OPC proportioned with efficiency factor (k-value); less cement than OPC reference concrete, compressive strength and 28 day normalized growth curves as a function of fly ash.
Seasonal Influence on FA:OPC Blended Concretes (Curing Temperature)

The seasonal effect of curing conditions (summer vs winter) was also investigated and the data is shown in Figure 7. As is seen at fixed water binder ratio OPC concrete 28 day compressive strengths are lower in cylinder specimens moist cured under hot conditions compared to cooler conditions, with early age strength enhanced. In the case of FA proportioned concrete with the efficiency factor (k-value) compressive strengths are enhanced at all ages (including 28 days plus) in hot conditions compared to cold conditions.

This strongly indicates that concrete produced in summer with FA could mitigate the seasonal fluctuations in concrete 28 day compressive strengths with OPC concrete (alone) throughout the year.

**Figure 7.** Seasonal effect of concrete compressive strength (curing temperature).
Seasonal Influence on Concrete (Batching Temperature)

The seasonal effect of batching conditions (summer vs winter) was also investigated and the data is shown in Figure 8. As is typically seen there is reduced workability (slump) in concrete made in hot conditions compared to cold conditions at fixed water/binder ratio. This would necessitate either increasing the amount of water reducing admixture, or FA (as a mineral admixture) or water (to the detriment of concrete strengths). The effect of adding additional water only above the mix design to maintain the slump on the concrete strength is show in the figure below.

![Concrete Slump vs Ambient Batching Temperature](image)

**Figure 8.** Seasonal effect on concrete workability and added water above mix design.

High initial rate of hydration of OPC due to increased temperature retards the subsequent hydration and produces a non-uniform distribution of the products of hydration. Its this reason at high initial rate of hydration, there is insufficient time available for the diffusion of the products of hydration away from the cement particle and for a uniform precipitation in the interstitial space. All this results in concentration of the products in the vicinity of the hydrating particles which causes subsequent retardation in hydration and effects strength.

The reaction between the silicate phases, alite (C₃S) and belite (C₂S) of OPC and water is typically expressed as:

\[
2\text{Ca}_3\text{SiO}_5 + 6\text{H}_2\text{O} \rightarrow 3\text{CaO.2SiO}_2.3\text{H}_2\text{O} + 3\text{Ca(OH)}_2
\]  
Equation 7

\[
2\text{Ca}_2\text{SiO}_4 + 4\text{H}_2\text{O} \rightarrow 3\text{CaO.2SiO}_2.3\text{H}_2\text{O} + \text{Ca(OH)}_2
\]  
Equation 8

Calcium silicate hydrate (C-S-H) is the main product of the hydration of OPC and is primarily responsible for the strength in cement based materials. Concretes partitioned with FA continue to gain in strength relative to OPC concrete at later days due to the pozzolanic reaction of the FA with portlandite (calcium hydroxide) producing yet more/stronger calcium silicate hydrate (C-S-H):

\[
\text{Ca(OH)}_2 + \text{Si(OH)}_4 \rightarrow \text{CaH}_2\text{SiO}_4.2\text{H}_2\text{O}
\]  
Equation 9

Note: in C-S-H the hyphenation denotes the variable stoichiometry.
In addition the pozzolanic reaction is further accelerated at increased temperatures resulting in higher later day strength gains.

The efficiency factor \((k\text{-value})\) for class F FA with Ultracem OPC at 28 days in this study as a function of FA proportioning are presented in Figure 9. As can be seen the \(k\)-value decreases (to a point) with increasing amounts of FA; as has been shown in the literature. The \(k\)-value at higher FA proportions 25–35 % is ~0.5 which compares well with the \(k\)-value stated in EN 206-1 of 0.4 for CEN I 52.5N cement. At lower proportions of FA the \(k\)-value approaches 1 (equivalent to OPC).

![Figure 9. Efficiency factor (k-value) of fly ash as a function of proportioning.](image)

The accepted BS EN 206-1 value of 0.4 could be seen as a conservative value to cover various qualities, classes of FA and as a starting point for mix design optimization. The literature has shown that the \(k\)-value increases with increasing levels of silica content of the FA. Indeed class F FA has higher levels of silica (and lower CaO) than class C FA for example.

**CONCLUSIONS**

In practice the concept of an efficiency factor for the supplementary cementing material (SCM) can be applied in order to predict the performance of concrete incorporating fly ash. The efficiency factor \((k\text{-value})\) is defined as the part of the SCM in an SCM-concrete that can be considered as equivalent to cement.

Concrete slump decreased with an increase in concrete temperature with fixed water binder ratio. Increasing the water content without increasing the cement content is one of the reasons for reductions in strength during hot weather.

Curing in hot weather has a negative impact on ordinary Portland cement concrete late day strengths (with enhanced early age strengths).

Curing in hot weather has a positive impact on fly ash concrete late day strengths.

Fly ash concretes continue to gain in strength at 28 days plus compared to OPC concrete due to the pozzolanic reaction.
ACKNOWLEDGEMENTS

REFERENCES