Fly ash as supplementary material in concrete: A review

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Abstract. The use of supplementary cementitious materials such as fly ash has seen a steady growth among the recent studies as an economical and effective solution for partial cement replacement. A challenging issue when replacing cement is that the supplementary materials affect concrete properties differently according to various factors such as: the grade of cement, the percentage of replacement, curing periods and environment condition. In order to determine how the concrete compressive strength and its rheological properties can be affected by fly ash, a review on the previous study on concrete fly ash mixtures subjected to various experimentation factors in terms of its main properties has been carried out. The outcomes showed that low calcium fly ash content increases concrete compressive strength of hardened concrete for a period ranging between 28 to 56 days and enhances the concrete rheological properties when the substitution percentage is not too high. Consequently, when fly ash is used as a substitute of cement with a medium quantity, it has an economical and sustainable effect on the cement and concrete industry.

1. Introduction

The initiation of the use of “fly ash” term began in 1930 but it was only in 1937 that fly ash was reported by Carlson et al. [1] to be utilized in concrete in North America. The Hungry Horse Dam was the first structure that used fly ash during its construction in 1948. With the rising energy cost that happened between World War II and 1970, the interest toward fly ash grew and became apparent. Few years later, in 1980 the production of ash around the globe went beyond two hundred in the seventies in which fourteen percent of it was utilized in concrete. In 1989 the production raised to 561 metric tonne with 16% used in concrete industry. Compared to the previous report of 1977, the utilization of fly ash in concrete increased by three times during the following years.

After performing various tests, Giacciao and Malhotra [2] showed that the durability of the concrete diminishes when a high percentage of cement is substituted by fly ash. According to CANMET [3] cement can be substituted with a high proportion of fly ash only when the early compressive strength is not required. Padhye et al. [4] chose to perform an experimentation program using higher proportions of fly ash with various high grade cements to see the effect on the compressive strength of concrete. Padhye et al. [4] noticed that when substituting cement by more than 40% by fly ash, the compressive strength reduces especially at early ages, on the other hand, fly ash can be substituted for more than 40% if it is mixed with high grade cement which will provide an economical alternative for some design mixes. Davis [29] has explored the potential and benefits of fly ash in the manufacturing of concrete pipes and found significant positive benefits such as: concrete permeability is decreased which is
extremely important in concrete pipes, increasing resistance against weak acids, increased concrete cohesiveness which make it last longer and reduce the need of replacement.

When Portland cement is mixed with water an augmentation of warmth happens which leads to a rising the concrete temperature [12]. Koo et al. [11] highlighted the importance of diminishing this increase in temperature especially in mass concrete through the use of effective methods. Crown et al. [13] found when comparing the use of 25% low calcium with 20% high calcium ash, that the low calcium generates less heat than class C or Portland cement which made it the main reason for why ASTM class F was used as a supplementary cementitious material. The temperature rise depends on different factors; Owens et al. [14] looked on how sizes of different elements can affect heat hydration and the temperature increases as the proportion and the size augmented.

Fly ash is known for his ability to reduce water requirement in concrete mixtures but on the other hand its pozzalic reaction is slower which may delay the setting time of concrete. Klieger et al. [9] found that low calcium fly ash confronted to low temperature curing gives a better compressive strength than the high calcium ash. Malhotra [10] reported that for high percentage of ash to be used as its full potential, at least a period of 7 days of curing is necessary, if cannot be provided then the quantity of ash must be reduced.

Cook et al. [7] performed a comparison between mixtures with various high calcium fly ash with and without air-contained. They found that the rate of strength is nearly similar to the controlled concrete without ash. Smith et al. [8] chose to substitute not the cement but a proportion of the fine aggregates with an ASTM class C and discovered a noticeable increase in strength varying from 6.2 to 16% for a period varying between 28 to 56 days. Klieger et al. [9] were interested in the response of two types of ash on the compressive strength of concrete when this one is subjected to curing, moisture availability and low temperature factors.

Carlson et al. [1] noticed that when low calcium fly ash replaced cement partially, it decreases the quantity of water for cement hydration which improves the workability of the mixture. Brown [16] went deeper in the subject of workability by replacing this time not cement but aggregate or sand, he found that the workability improves as long as the replacement percentage does not exceed 8%. Brown [16], while experimenting on four concrete mixes containing various fly ash proportions, discovered that when increasing the ash percentage by 10, the compacting factors follows by 4% each ten times.

It is known that when harsh aggregates are used for concrete mixes, bleeding is highly to be noticed after the hardening phase. Copeland [17] accounted that bleeding reduced when fly ash as was used as cement replacement in harsh mixtures and provided even an improved finish paste to the blend.

Augmenting fly ash proportions of replacement has consequences, the concrete strength at early ages is reduced and the setting time slows which makes the construction process delay. Thus, this paper review based the previous study on the use of fly ash as supplementary cementation material and its various effects on concrete strength and its rheological properties at different percentages and summarize the enhancements that this material provides for a proper use.

2. Fly ash as supplementary cementitious material
Over the past years, CANMET [3] has been performing several researches about the effects on the use of fly ash for replacing cement but yet no documentation could be found on how much the appropriate percentage of ash that should substitute cement is. CANMET[3] investigated the outcomes on concrete when a high percentage of low calcium fly ash replaces cement, their results were deeply explored by Malhotra [2] which found after performing 3 different types of testing that when a high proportion of low calcium fly ash (ASTM class F) replaces cement, it offers three main advantages. The first one, after comparing the results regardless of the dilatation of concrete mixed with coarse aggregate, high proportion low ash mixtures presented no dilatation in comparison with the two controlled non ash concrete. After that Malhotra [2] noticed due to the dense structure of low calcium fly ash, concrete becomes high impermeable against chloride ions. And finally, when low calcium fly ash concrete is subjected to low then high temperature changes for 6 cycles for 24 hours, it showed a more durable concrete compared to a non-ash concrete.
Padhye et al. [4] noticed that most past researches about fly ash involved only small proportions replacement with low grades of cement. For this reason, they decided to experiment various ash proportions replacement with high grade concretes (M30, 40, 50) to see its impact on the concrete compressive strength while confronting their mixtures to various curing periods. Padhye et al. [4] found after various testing that while increasing the proportion of ash, the early strength of the mixtures diminished compared to a non-ash blend. The agreed-on fly ash can be considered as cement replacement alternative as long as its proportion does not exceed 40%. They observed that some blends of low proportion high grade cement mixed with a high quantity of ash can be more economical than low proportion of ash with high quantity of low grade cement.

3. Categories of fly ash
Fly ash can be divided in two categories: ASTM class C: fly ash with high calcium produced from lignite of subbituminous coals; and ASTM class F: fly ash with low calcium percentage and normally produced from bituminous coals, ASTM [5]. According to various studies, only high calcium fly ash affects the rate of strength development in concrete at later ages.

4. Effect on concrete strength
The first fly ash that was used as a cement replacement is ASTM class F, a low calcium fly ash. Class F contains a high quantity of unburned bituminous coal, produced from old power plants. Lamond [6] noticed when fly ash is used as cement replacement, the concrete strength results showed a reduction rather than an expected increase that led to a conclusion: fly ash reduces concrete strength. After the discovery of the second type of fly ash, many researchers started to try understanding the factors affecting the strength of fly ash concrete.

It has been mentioned by various studies that the rate of strength development of concrete is affected only by the high calcium fly ashes at later ages. For this reason, Cook et al. [7] compared two control mixtures that do not contain fly ash and with mixtures that have different high calcium percentages with and without air entrained concrete. The percentage replacement use is 0, 20, 30 and 50. The details of their mixture are presented in Table 1 and their results are shown in Figure 1. From the results in Figure 1, the mixtures with high percentages of ash show more strength at later age (90 days) than the one without.
Figure 1. Results of compressive strength when concrete is mixed with ASTM class C fly ash [7]

Table 1. Mixture details incorporating high calcium fly ash [7]

| Mixture designation | C1 | C2 | C3 | C4 |
|---------------------|----|----|----|----|
| Proportion (kg/m³)  |    |    |    |    |
| Cement              | 387| 309| 272| 196|
| Fly ash             | 0  | 77 | 117| 196|
| Cement + fly ash    | 387| 386| 389| 392|
| Water               | 145| 145| 146| 147|
| Coarse aggregate    | 1146| 1144| 1153| 1160|
| Fine aggregate      | 701| 690| 678| 654|
| Properties          |    |    |    |    |
| Slump               | 3  | 9  | 12 | 21 |
| Air content         | 2.1| 1.9| 1.9| 1.4|
| Unit weight         | 2377| 2364| 2364| 2352|
| Fly ash as percentage of cement | 0 | 20 | 30 | 50 |

Smith et al. [8] decided to replace a fine aggregate volume with a high calcium fly ash while keeping the proportion of the cement and the coarse aggregate constant. Their result as shown on Table 2, demonstrate a compressive strength increase varying from 6.2% to 16% for a period ranging between 28 and 56 days.
Table 2. Compressive strength due to ASTM class C fly ash [8]

| Cement (kg/m³) | Fly ash (kg/m³) | Compressive strength<sup>a</sup> | Percentage of control values | Gained (%) |
|---------------|----------------|-------------------------------|-----------------------------|------------|
|               |                |                               | 28 days | 56 days | 28–56 days |
| 91            | 50             | –                             | 354    | 393     | 15.2       |
| 68            | 77             | –                             | 435    | 494     | 13.6       |
| 136           | 50             | 210                           | 228    | 256     | 10.2       |
| 68            | 77             | 245                           | 269    | 274     | 11.1       |
| 182           | 50             | 149                           | 155    | 167     | 8.2        |
| 59            | 153            |                               | 163    | 177     | 12.0       |
| 68            | 77             | 149                           | 155    | 167     | 12.0       |
| 77            | 187            |                               | 190    | 249     | 6.2        |

<sup>a</sup> In these mixes, fly ash was used to replace fine aggregate

Klieger et al. [9] assessed the response of the two different types of fly ashes on concrete compressive strength facing various curing conditions, accessibility of moisture and coldness. They noticed that the class doesn’t have a high impact on the long term compressive strength without introducing the curing factor. The results showed that concrete with low calcium fly ash when confronted to coldness curing gives a better compressive strength than a high calcium or concrete control facing the same condition. Klieger et al. [9] concluded high calcium fly ash and control concrete required less moist curing for long term strength development compared to class F. on the other hand they noticed that the two types of fly ash were more sensitive to the availability of moisture at later ages than the control concrete. According to Malhotra [10] the use of a large percentage of ash requires the concrete to be cured for a starting period of 7 days extended to even 14 days, when this condition cannot be satisfied the quantity of ash must be diminished to benefit of the full potential of fly ash.

5. Fly ash affects temperature of fresh concrete

Immediately after cement is mixed with water, concrete is followed by a rising amount of hydration heat due to cement hydration reactions which can lead to surface cracking, therefore effective collings methods are crucial to avoid this issue especially in mass concrete, Koo et al. [11]. The substitution resulted in decreasing the temperature augmentation, which was one of the main reasons why fly ash was used in the construction of the Hungry Horse Dam, Philleeo [12]. The information recorded by Crown et al. [13] shows that a concrete with twenty five percent ASTM class F generates less hotness compared to a 25% high calcium fly ash or a Portland cement as shown in the Figure 1.
The temperature rise in concrete depends on different factors, such as the properties of the concrete used or the environment surrounding it. Owens et al. [14] chose to investigate on a possible relation between heat augmentation in ash mixtures and the member dimensions. They reported their estimation data through the Figure 3. The figure shows that the temperature rises as the dimensions and the proportion of fly ash follows.

**Figure 2.** Increase of temperature due to ASTM C and ASTM F [18]

**Figure 3.** Responses of element’s dimensions on the increase in temperature in fly ash concrete [15]
6. Rheological properties of fly ash concrete

Carlson et al. [1] found that ASTM class F influences the rheological properties of cement pastes by reducing the quantity of water needed of the mixture compared to the other pozzolans that behave otherwise, which increases the workability of the mixture. Owens [14] found that the percentage of coarse with particles > 45\(\mu\)m is main factor to workability improvement with a substitution that should be less than 50%. The results are shown in Figure 4.

![Figure 4. Coarse particle effect on the quantity of water of the mixture [15]](image1)

Brown [16] tested four concretes where fly ash was used as supplementary cementitious material. The results are presented in Figure 5, show that the increase of cement replacement percentage, the compacting factor and the workability improved. Brown [16] noticed by increasing the percentage of ash by 10, the compacting factor increased by 4%.

![Figure 5. effect of fly ash on the workability of the mixture [16]](image2)
Brown [16] experimented this time, the substitution of aggregate or sand by different percentages of fly ash to determine the impact on the workability. As shown in figure 6, Brown [17] noticed that when the percentage of replacement exceeds 8, the workability reduces until it becomes unusable for a 40% replacement.

![Figure 6](image)

Figure 6. fly ash Influence when substituting sand or aggregate on the workability of the mixture [17]

It was reported that concrete made from harsh aggregates will produce bleeding especially with lack of fine. Copeland [17] reported that the use of fly ash reduces bleeding in harsh mixtures. Some type of fly ash gives improved finish when used as replacement especially with harsh mixtures lacking of fines.

7. Conclusion
1. Large percentage of low calcium fly ash provides concrete with high permeability against the passage of chloride ions, better durability and low dilatation.
2. Fly ash used as cement replacement in high concrete grades decreases the compressive and early strength of these grades. Fly ash can be an economical solution that gives better 28 days strength by mixing a small portion of high grades concrete with a high fly ash percentage rather than a big quantity of low grade concrete with low ash percentage.
3. The rate of strength development of concrete is affected only by high calcium fly ash at later ages, when fine aggregates are substituted by the ASTM class C. concrete strength shows an increase of 6.2 to 16% for a period varying between 28 to 56 days.
4. The substitution of cement by ASTM class F generates less heat in fresh concrete compared to a high calcium ash, which made it the main reason of its use in the hydraulic construction.
5. ASTM class F influences the rheological properties of cement pastes as it increases the workability of the concrete mixture and reduces its water requirement.
6. The workability of a mixture where fly ash replaced sand or aggregates reduces if it exceeds 8% replacement and becomes unworkable if it reaches 40%.
7. Fly ash reduces bleeding due to lack of fines in concrete made of harsh aggregates.
8. When substituting cement by 10%fly ash the compacting factor increases by 4% for each ten percent addition.
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