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# A Preliminary Study on Cracking Tendency of Cement Paste Incorporating High Calcium Fly Ash

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**Abstract.** Fly ash is a waste material from burning coal that can be used to reduce the amount of cement in making concrete and to improve the characteristics of concrete. Besides being able to improve the flowability of fresh concrete, fly ash can also serve to reduce cracking of concrete. But in certain cases, cement paste incorporating fly ash type C (high calcium fly ash) experiences cracks, right after being released from formwork. The purpose of this study were to investigate the causes of cracking of cement paste incorporating fly ash type C, the influence of fly ash variations, and the countermeasures. The evaluation conducted for this experiment were based on visual inspection and compressive strength test of cement paste at 28 days. Test specimens were made in the form of cement paste with fly ash content of 50%, by mass. Fly ash used was of type C taken from three different batches from one source; with fly ash type F from three different sources used for control specimens. Superplasticizer, silica fume, and calcium carbonate were used as additives to evaluate their effect in mitigating cracks. The results show that the use of fly ash type C may cause cracks on the surface of hardened paste. Fly ash content, especially CaO and MgO, are the key factors affecting the cracks tendency on the surface of cement paste, due to expansion. Superplasticizer and silica fume can be used to mitigate cracks of cement paste.

## Introduction

Fly ash is a waste product from the power plant. It is produced from the combustion of coal in the form of spherical solid particles. Its small particle size and high silica content enable fly ash to be used as pozzolanic material in concrete mixture. There are lot of studies that have been done to utilize fly ash as cement replacement in concrete mixture; for example as source material for manufacturing geopolymer concrete [1], and for making high volume fly ash (HVFA) concrete [2].

One problem that often arises in the manufacture of concrete is cracking, caused by several factors such as temperature, environment, and material components itself. Autogenous shrinkage is a type of cracking that commonly occur in the early age of concrete [3]. Incorporating fly ash in concrete mixture has been reported to reduce the rate of cracking in concrete [4-5]. The use of slag and fly ash in concrete mixture reduces the heat of hydration of concrete, and thus prevents the occurrence of cracks due to heat of hydration in the early age of concrete [3].

However, during a pilot study conducted in the laboratory, a problem associated with samples experiencing cracks right after being released from formwork was discovered. The cracks occurrence only happened when fly ash type C (high calcium fly ash) was used in the mixture. Cracks appeared on the surface of one or more of mortar/paste samples. Therefore, this study is aimed to investigate causes of the cracks on cement paste incorporating fly ash type C, to evaluate the effect of cracks on compressive strength and to look for some alternative measures to mitigate the occurence of cracks.

## Experimental Work

**Materials.** Portland Pozzolan Cement (PPC), Ordinary Portland Cement (OPC), fly ashes type C and F were used as the binding material, whereby type F was used for the control samples. Fly ash type C was obtained from three different batches from one power plant (designated as C1, C2 and C3), while fly ash type F was acquired from three different power plants in Indonesia (indicated as F1, F2, and F3). CaO contents of fly ashes type C are in the range between 10-20%, by mass, of the total content of fly ash as measured by X-ray fluorescence (XRF), while for type F is smaller than 10% (see Table 1). The results from particle size analysis (PSA) can be seen in Figure 1. Superplasticizer (SP), silica fume (SF), and calcium carbonate ($CaCO_3$) were used as additional material, intended for reducing cracks.

Table 1. Chemical Composition of Fly Ash

| Component | Fly Ash [%] | | | | | |
|---|---|---|---|---|---|---|
| | F1 | F2 | F3 | C1 | C2 | C3 |
| $SiO_2$ | 50.14 | 51.20 | 38.24 | 39.78 | 37.58 | 36.16 |
| CaO | 4.03 | 5.54 | 9.15 | 15.47 | 16.33 | 17.67 |
| $Al_2O_3$ | 29.08 | 18.90 | 15.28 | 17.87 | 17.35 | 17.38 |
| MgO | 1.11 | 3.17 | 5.19 | 6.45 | 6.68 | 7.48 |
| $Fe_2O_3$ | 9.66 | 17.71 | 24.28 | 15.00 | 14.17 | 14.09 |
| $Na_2O$ | 0.79 | 0.63 | 0.80 | 1.51 | 2.96 | 2.49 |
| $SO_3$ | 0.77 | 0.47 | 0.60 | 1.32 | 1.58 | 1.51 |
| $K_2O$ | 1.53 | 0.82 | 0.78 | 1.32 | 1.33 | 1.20 |
| Other | 2.89 | 1.56 | 5.68 | 1.28 | 2.02 | 2.02 |

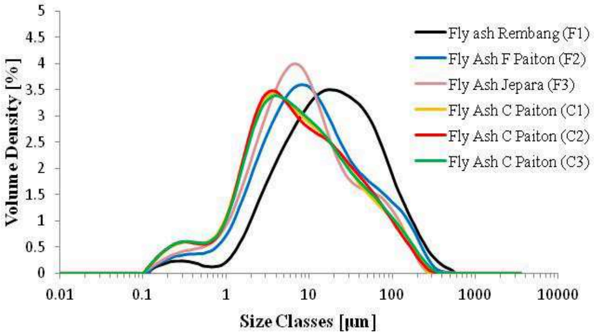

Fig. 1. Particle Size Distribution of Fly Ash

**Mixture Proportion.** The samples were of cement paste cubes, size 5x5x5 $cm^3$, and the experiment was divided into two phases. Water to cementitious ratio for both phases was taken constant at 0.3. On the first phase, cement paste was prepared using a combination of PPC and fly ash type C (C1 and C3) as the cementitious material. The percentage of fly ash used was in the range of 30-70% of the total cementitious material, by mass. In addition, another mixture of cement paste consisting of 70% cement and 30% fly ash C3 was prepared, with water to cementitious ratio of 0.2, added with SP in the amout of 0.5-1.0% of the total cementitious material.

On the second phase, six types of fly ash were used as partial substitute for cement in the paste mixture, i.e. three types of fly ash type C (C1, C2 and C3) and three types of fly ash type F 3 (F1, F2 and F3). The type of cement used was OPC and fly ash was incorporated in the amount of 50% of the total cementitious material, by mass. The details of the mixture proportion are shown in Table 2 and Table 3.

Table 2. Mixture Proportion for First Phase

| % FA | PPC [kg/$m^3$] | Fly Ash [kg/$m^3$] | Air [liter/$m^3$] |
|---|---|---|---|
| 0 | 1692 | - | 508 |
| 30 | 1184 | 508 | 508 |
| 40 | 1015 | 677 | 508 |
| 50 | 846 | 846 | 508 |
| 60 | 677 | 1015 | 508 |
| 70 | 508 | 1184 | 508 |

Table 3. Mixture Proportion for Second Phase

| % FA | OPC [kg/$m^3$] | F1 [kg/$m^3$] | F2 [kg/$m^3$] | F3 [kg/$m^3$] | C1 [kg/$m^3$] | C2 [kg/$m^3$] | C3 [kg/$m^3$] | Water [liter/$m^3$] |
|---|---|---|---|---|---|---|---|---|
| 0 | 1692 | - | - | - | - | - | - | 508 |
| 50 | 846 | 846 | - | - | - | - | - | 508 |
| 50 | 846 | - | 846 | - | - | - | - | 508 |
| 50 | 846 | - | - | 846 | - | - | - | 508 |
| 50 | 846 | - | - | - | 846 | - | - | 508 |
| 50 | 846 | - | - | - | - | 846 | - | 508 |
| 50 | 846 | - | - | - | - | - | 846 | 508 |

Additionally, more samples were made incorporating silica fume and calcium carbonate as admixtures, in the amount of 10% of total cementitious material. Mixture proportion of paste can be seen in Table 4. Curing was carried out by immersing the hardened samples into the tap water pool.

**Testing.** Visual inspection was conducted to evaluate the crack tendency on the surface of the hardened paste samples. Relative density for each sample was obtained by comparing the actual mixture density (d) with the theoretical mixture density (do) [6]. Flowability testing was carried out by using a flow table apparatus. Compressive strength test was done when the samples reached the age of 28 days using a universal testing machine.

Table 4. Mixture Proportion of Paste with the Addition of Silica Fume and Calcium Carbonate

| % FA | OPC [kg/m$^3$] | C1 [kg/m$^3$] | C2 [kg/m$^3$] | C3 [kg/m$^3$] | CaCO$_3$ [kg/m$^3$] | SF [kg/m$^3$] | Water [liter/m$^3$] |
|---|---|---|---|---|---|---|---|
| 50 | 846 | 846 | - | - | 169.2 | - | 508 |
| 50 | 846 | 846 | - | - | - | 169.2 | 508 |
| 50 | 846 | - | 846 | - | 169.2 | - | 508 |
| 50 | 846 | - | 846 | - | - | 169.2 | 508 |
| 50 | 846 | - | - | 846 | 169.2 | - | 508 |
| 50 | 846 | - | - | 846 | - | 169.2 | 508 |

## Results and Discussion

**Relative Density, Flowability, and Compressive Strength.** The first phase aims to evaluate the effect of high calcium fly ash content on the relative density and 28-day compressive strength, as shown in Fig. 2. Values obtained from flowability test showed that as the percentage of high calcium fly ash in the mixture increases, the flow diameter of the fresh mixture is also increased. The flow diameters are in the range between 20-25cm.

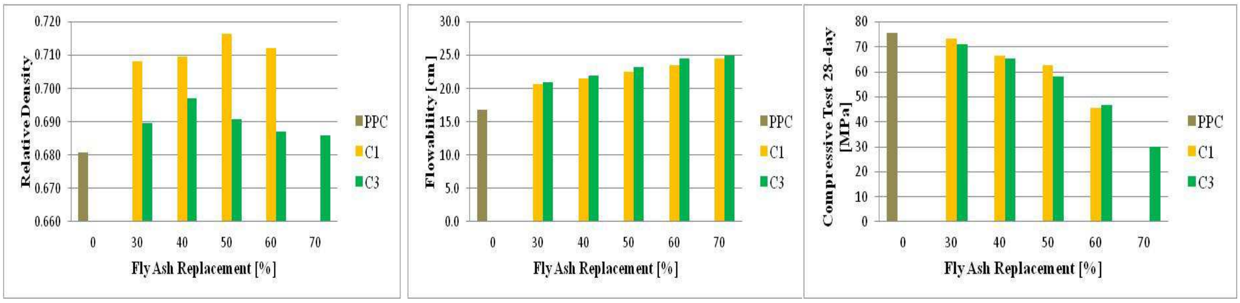

Fig. 2. Relative Density (left), Flowability (middle), Compressive Strength at 28th-day (right) of Cement Paste with Various Fly Ash Type C Content

The higher the relative density value closer to one indicates the denser the paste mixture. The relative density values of the hardened paste obtained from the incorporation of two types of fly ash C1 and C3 show the tendency to increase with the increase of fly ash content up to 50%. Beyond that, the values are decreased. The decrease of relative density indicates that the fly ash content in the paste mixture is too much, from the point of view of achieving the highest relative density. On the compressive strength, paste using fly ash C1 and C3 does not show any significant difference, although the ones using fly ash C1 with sligtly higher $SiO_2$ content tend to have higher strength, due to higher pozzolanic potential [7].

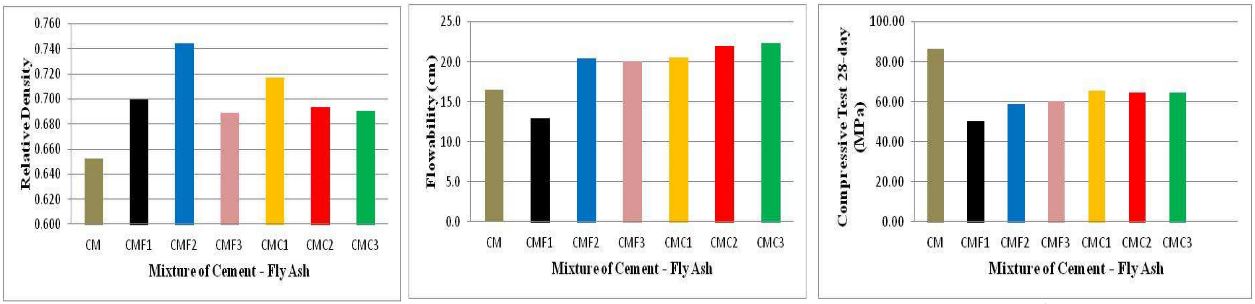

Fig. 3. Relative Density (left), Flowability (middle), Compressive Strength at 28th-day (right) of Cement Paste Incorporating Fly Ash Type C and F

On the second phase of this study, three types of class-F fly ash and three types of class-C fly ash were used, with the fly ash content was set constant at 50%. This phase aims is to evaluate the effect of using fly ash on surface cracks of the hardened paste. In addition, besides evaluating the cracks that occur, an evaluation on the properties of the cement paste is also carried out, as shown in Fig. 3.

Mixture showing the highest relative density values is mixture using fly ash F2 (CMF2), while the lowest value is for the one using fly ash F3 (CMF3). This is influenced by the difference in particle size distribution of fly ash. Flowability values of all mixtures of cement paste with fly ash type C (CMC1, CMC2 and CMC3) and type F (CMF2, and CMF3) are similar, except for the one using fly ash F1 (CMF1), which shows the lowest value. This is because fly ash F1 (CMF1) has larger particle size than the other fly ash.

On the compressive cement, paste with only OPC cement (CM) shows the highest compressive strength. This is because pozzolanic reaction with calcium hydroxide takes longer time to produce CSH [8]. Paste utilizing fly ash type C (CMC1, CMC2 and CMC3) tends to have higher compressive strength at 28th day, compared to the ones with fly ash type F (CMF1, CMF2, and CMF3). This is because a fairly higher CaO content in fly ash type C react with water to produce calcium hydroxide (CH) and increase the compressive strength at early age [9].

**Crack Tendency on Cement Paste Incorporating Fly Ash.** There is a tendency that crack occurs on the surface of cement paste right after being released from moulds. It happens especially on those incorporating fly ash type C or high calcium fly ash, whereby its CaO content is higher than 10%. Crack appearance on the surface of hardened cement paste is shown in Fig. 4. The tendency does not happen when fly ash type F is used. The frequency of crack presence on the surface of paste varies, and tends to be arbitrary. Replacing PPC with OPC does not alter the cracks emergence. This indicates that the use of fly ash type C in the paste mixture can lead to cracking on the surface of hardened cement paste.

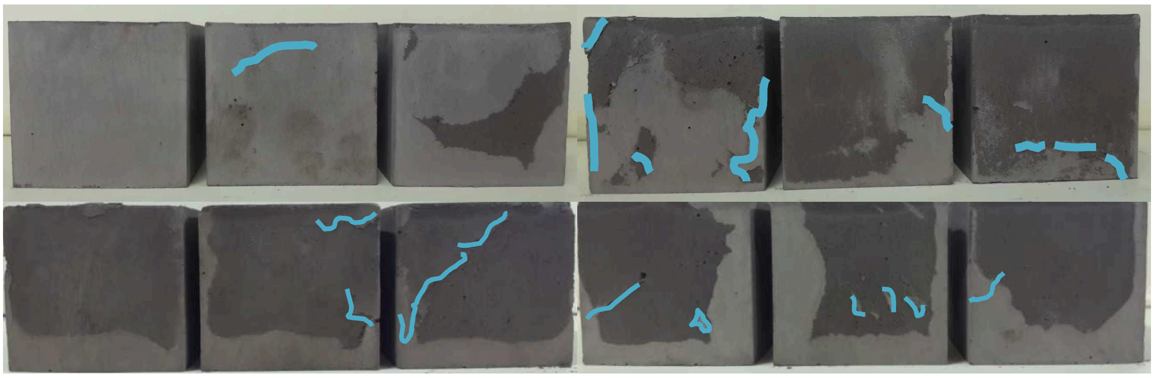

Fig. 4. Crack Appearance on the Surface of Cement Paste Containing Fly Ash type C

Cracks on the surface of cement paste tend to occur only on one or two sides of the cubes. This is caused by the uneven distribution of heat of hydration and reaction of fly ash particles. Some sides of the cube tend to be very dense, whereas for the other are less [10]. The variation in the speed of reaction and hydration in the cement paste containing fly ash related with its chemical composition [11]. In this study, the reaction of type C fly ash may occur due to the high content of CaO in fly ash. This can be the cause of cracks occurrence on the surface of cement paste. In addition, other substance such as MgO and $SO_3$ can also be the cause of cracking in cement paste [12].

**Effect of CaO Content on Cracking.** XRF test results show that the three types of fly ashes type C used in this study have fairly high CaO content, i.e. higher than 15%. This can be one of the causes of cracks development [13]. Cement and CaO content in fly ash react with water and causing different heat of hydration inside the mixture. The difference of heat may cause the volume instability [7] and excessive expansion of the cement paste, which leads to cracking. Increase content of CaO in fly ash may cause cracks occur more often, due to increase in the expansion of the cement paste [14].

**Effect of MgO Content on Cracking.** MgO can contribute to crack development on the surface of cement paste. High MgO content above 5% can increase the expansion of cement paste. This is because MgO can reduce the amount of $Al_2O_3$ in the mixture. $Al_2O_3$ is a compound that can reduce the expansion of the cement paste [3]. Table 1 shows that the levels of MgO content in fly ash type C used in this study are above 5%, and thus – most likely - increases the tendency of cracking on the surface of cement paste. MgO can be a suspect as a cause of cracks on the surface of the cement paste incorporating fly ash type C or high calcium fly ash.

**Effect of Superplasticizer, Silica Fume, and Calcium Carbonate.** Samples produced in first phase of the experiment containg fly ash type C and with the addition of superplasticiser, do not show any crack on the surface of the hardened paste. Heat of hydration in cement paste can be reduced with the addition of superplasticizer [15]. Reduction in heat of hydration simultaneously reduces the expansion and minimize the appearance of cracks. Silica fume can cause shrinkage on the surface of paste [16]. Samples of cement paste with the addition of silica fume tend to not having any crack on the surface. Cracks on the cement paste containg fly ash type C occur because of the expansion. The addition of silica fume in the mixture causes shrinkage; that minimizes the expansion, and thus lowers the crack development. Samples with additional calcium carbonate still produce cracks on its surface. This is because calcium carbonate generates heat of hydration on cement mixture [17]. The addition of calcium carbonate in the mixture will increase the heat of hydration, increase the expansion and lead to crack on the surface of cement paste.

## Conclusion

From this preliminary study, it can be concluded that:

- The use of fly ash with high CaO content of more than 10% in a cement paste mixture can result in cracks on the surface of hardened paste right after being released from the moulds.
- Crack development is caused by the expansion of the cement paste containing fly ash type C.
- The cracks are most probably caused by uneven distribution of heat of hydration due to high CaO content in the mixture.
- MgO content in the fly ash which is higher 5% can be one contributing factor to cause expansion on the cement paste containing fly ash type C.
- The high levels of CaO content in the fly ash may increase the frequency of crack appearance on the surface of cement paste.
- Addition of superplasticizer and silica fume can reduce the rate of expansion in the cement paste containing fly ash type C with high CaO content.
- The addition of calcium carbonate cannot reduce the appearance of cracks, because the presence of calcium carbonate may increase the uneven distribution of heat of hydration in the cement paste containing fly ash type C.

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