Effect of fly ash to water-cement ratio on the characterization of the concrete strength

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Abstract. Fly ash (FA) is a burning coal product which is used as supplementary cementitious materials (SCM) as the conjunction with cement. The use of FA is considered by its pozzolanic properties i.e. SiO\textsubscript{2}, Al\textsubscript{2}O\textsubscript{3} and CaO to hardened concrete. The potential of FA as SCM has been well-known over the globe but that significant utilization has to be studied based on its compound’s characteristics and pozzolanic activity. For this case, the amount of FA is added 30\% by mass of total cementitious material, concrete with fly ash (NFA) and another blended without FA as normal concrete (NC) made of ordinary Portland cement. This amount is indicated as dosage in moderate to high volume of FA classification. This replacement pairs with water to cement ratio (W/C) with the value of 0.47 and 0.30 e.g., NC1, NC2 and NFA1, NFA2, respectively. These W/C uses considering effect FA on water demand of concrete proportioned for equal slump. The results showed that NC\textsubscript{2} and NFA\textsubscript{2} in the age of 28-day inform higher compressive strength, 30\% and 28\%, respectively. Another indication from the comparison of NC2 and NFA2 were also in good agreement that the use of FA decrease the compressive strength around 3\% to 6\%.

1. Introduction
Fly ash (FA) is a coal combustion residual which appears as a by-product from processing combustion in steam generator of industrial thermal power plants. The amount of FA is enormously cause serious problems which is related to the environment pollution [1]. Figure 1 inform the increasing cases which is factories pulverized the FA in each year. In fact, the problem is now successfully solved to use a pollutant of FA as a replacement of cement. Many researchers studied the variety of FA in the mixture composition to substitute cement started in low dosage to very high dosage [2]–[4]. Historically, most common used of FA in concrete normally at levels ranging from 10\% to 25\% by mass of the cementitious materials but it still depends on the pozzolanic activity [5]. Many researchers give the assumption that type of FA is also considered by the location and production type of coal pulverisers which can be deficient between sources and collection methods[6]–[9]. This parameter condition effects the performance of FA in concrete that is followed by the influence of its physical and chemical properties. The most used specification is followed by ASTM C618 [10]. This specification characterises the FA into two clusters based on its chemical compound is illustrated in Figure 2. Due to the differentiation including the match of the raw material, very often, the potential of FA as a replacement does not meet the required standard.
In this case, the FA from PLTU Paiton Probolinggo is investigated. The mass pollutant product in this PLTU inevitable become a problem due the lack of distribution and allocation. The previous studies have been investigated the same FA but implying a low capacity with high dosage characterization [12]. In this current research, the dosage of FA will remain the same 30% from the total of cementitious materials using two composition of water to cement/binder e.g., 0.47 and 0.3 which is categorized as a high-volume dosage classification [0x0]. This classification of dosage levels of FA follows the recommendation of Portland cement association (PCA). The chemical compound will first be evaluated and followed to observe the concrete strength behaviour in variety of ages, 14-day, 28-day and 56-day.

1.1. Applications of FA in Concrete

The use of FA in the concrete construction was first designed for a mass concrete application where the early strength was required and where the condition of low-heat generation was implied [13]. The use of this concrete was also considered to support the durability by increasing its mechanical properties [11]. Figure 2 inform the chemical content with the amount of total oxides for FA class F over 70% and FA class C over 50% (SiO$_2$ + Al$_2$O$_3$ + Fe$_2$O$_3$) according to ASTM C618 [10].

FA is also favoured to concrete through the use of blended hydraulic cement consisting of Portland cement (PC), FA and other cementitious materials. One type of the concrete that well-paired with the optimization of FA is engineered cementitious composite (ECC) [14]–[17]. Blended cement containing
FA are widely available in Indonesia. Most industrial companies imply this composition to support the production and provide an affordable mixing portion. In addition to maximize the use of pollutant of FA which is considered as the biggest pollutant distributed by the process, known as 75% by product [18].

1.1.1. Effect of FA on the fresh concrete properties. In some cases, the use of superplasticizer is necessary due to a very low water content to obtain a workability. Various researchers have successfully produced the optimum composition of FA concrete using locally materials and admixture [19], [20]. It is mainly considered to the proportion of FA on the concrete mixture. A well-portioned mixture using FA will improve the workability when compared to PC concrete with the same slump. This is highlighted, with a given slump, FA concrete consolidates better than conventional PC. In addition, FA also advances the cohesiveness and lessen the segregation [21]. It is emphasizing that all the benefits of FA will only be grasped in well-portioned of concrete mixture. The fresh concrete properties are greatly influenced by the mixture compositions including the type and amount of cementitious material, water to content ratio, aggregate classification, the condition ofentrained air and the use of superplasticiser. One of the studies improved rheological properties of FA in high-volume has been conducted by Bouzoubaa (2001) [22], [23].

1.1.2. Effect of FA on the hardened concrete properties. Concrete is normally proportioned to achieve a certain minimum strength at specified age, 14-day, 28-day (typical age of the concrete) and 56-day. Figure 3 illustrates the effect on compressive strength of replacing a certain mass of PC with a low-calcium FA class C and managing a constant content of W/C. The early-age strength is decreased as the level of replacement increased. However, to maintain the development in a long term, the FA has to be controlled in each ages of strength and the quality control of curing has to be provided. The behaviour of FA development shows in the Figure 3 which strength parity with the PC is achieved is greater at higher lever of FA. The FA content can affect the ultimate of compressive strength.

2. Experimental methods

2.1. Test Specimens
A series of cylinder compressive strength specimens with two matrix constituents were made and tested in the concrete laboratory of ITATS in Surabaya. The specimens were used 300mm×150mm dimension and divided by the ages e.g., 14-day, 28-day and 56-day and tested by using electric hydraulic pump compression. Each age was distributed by using 3 specimens to give a proper behaviour. These specimens, hereafter referred to as NC and FA specimen which was concerned with two variety of W/C content, 0.47 and 0.30 namely NC1 and NC2 and also followed by NFA1 and NFA2. The FA was taken from PLTU Paiton Probolinggo which were categorized its chemical compound by using X-ray Fluorescence (XRF) using Rigaku RIX-3000 model (see Figure 5).

2.2. Material Properties and Fabrication
The concrete mixture used to fabricate the specimens are presented in Table 1. The mixtures for both NC and NF used two different water-to-cement ratios of 0.47 and 0.30, respectively. The materials were firstly confirmed their characterization follow the specification standard from various ASTM aspects (see Table 2). The coarse aggregate was taken from Pasuruan (Banyu Biru) with a maximum aggregate size of 20 mm, fine aggregate (Lumajang) with a size < 3 mm and PC (PCC-Gresik), and superplasticizer to help the workability. One mixing was conducted for 5 cylinders using automatic mixer with 0.1 m³ capacity.

Each specimen was casted into steel cylinder 300mm×150mm and then cured in fully submerged water. The fresh concrete before casting were poured to control the workability using slump cone test in accordance with ASTM C143 [24]. A summary of concrete compressive strength is accordance to ASTM C39 and presented in Figure 5 followed by the detail of each specimen in Figure 6 to Figure 11.
Table 1. Summary of concrete mixture and slump value

| Details                          | W/C 0.47 | W/C 0.3 |
|----------------------------------|----------|---------|
|                                  | NC1      | NFA1    | NC2       | NFA2    |
| Fine Aggregate (kg/m³)           | 628      | 628     | 628       | 628     |
| Coarse Aggregate (kg/m³)         | 1166     | 1166    | 1335      | 1335    |
| Cement (kg/m³)                   | 436      | 305.2   | 436       | 305.2   |
| Fly Ash (kg/m³)                  | -        | 130.8   | -         | 130.8   |
| Water (kg/m³)                    | 205      | 205     | 131       | 131     |
| Superplasticizer (g/m³)          | -        | -       | 5.6       | 5.6     |
| Slump (cm)                       | 12       | 14      | 10        | 12      |

Note: coarse aggregate is crushed granite in <20mm with fine aggregate <3mm

Table 2. Characteristic materials of fine and coarse aggregate compared to required standard

| Test                           | Fine Agg. | Req. standard | Coarse Agg. | Req. standard | Guideline code |
|--------------------------------|-----------|---------------|-------------|---------------|----------------|
| Moisture (%)                   | 2,1       | 1-5           | 1,62        | 1-5           | ASTM C 556-89  |
| Relative Density (gr/cm³)      | 2,67      | 1.6-3.3       | 2.78        | 1.6-3.3       | ASTM C 127-93  |
| Absorption Capacity            | 2,14      | Max 5         | 1.23        | Max 4         | ASTM C 556-89  |
| Bulk Density (Loose) (kg/dm³)  | 1,41      | 0.4-1.9       | 1.35        | 0.4-1.9       | ASTM C 29/C29M-91[25]|
| Bulk Density (Compact) (kg/dm³)| 1,54      | 0.4-1.9       | 1.5         | 0.4-1.9       | ASTM C 29/C29M-91|
| Mud content (%)                | 3,52      | 2.1           | Max 5       |                | ASTM C 117-95  |
| Organic Impurities             | No.3      | No.6          | -           | -              | ASTM C 40-92   |
| Fineness Modulus               | Zone 2    | 2<Fm<3,1      | Fm=7.3      | 6.5<F          | ASTM C 136-95A |
|                                | Fm=3,05   |               | 5           | m<8            | ASTM C 33      |

Table 3. Summary of compressive strength obtained from 300×150 mm cylinder

| Specimen            | NC1+NFA1 (days) | NC2+NFA2 (days) |
|---------------------|-----------------|-----------------|
|                     | 14   | 28   | 56 | 14   | 28   | 56 |
| Mean (MPa)          | 24.69 | 27.12 | 28.37 | 23.33 | 26.16 | 27.26 |
| Standard of deviation (SD in MPa) | 0.31 | 2.43 | 3.69 | 0.17 | 2.83 | 3.93 |
| Mean (MPa)          | 27.94 | 31.01 | 32.17 | 25.95 | 29.18 | 30.11 |
| Standard of deviation (SD in MPa) | 0.52 | 3.14 | 4.24 | 0.19 | 3.23 | 4.16 |

Figure 4. Chemical compound of Paiton FA class C

Figure 5. Average of compressive strength due to mixture proportioned
Figure 6. Compressive strength W/C 0.47 – 14 days

Figure 7. Compressive strength W/C 0.47 – 28 days

Figure 8. Compressive strength W/C 0.47 – 56 days

Figure 9. Compressive strength W/C 0.30 – 14 days

Figure 10. Compressive strength W/C 0.30 – 28 days

Figure 11. Compressive strength W/C 0.30 – 56 days
3. Results and discussion

A series of compressive strength of W/C 0.3, NC1 and NFA1 were listed in Figure 6 to Figure 8, and W/C 0.47, NC2 and NFA2 were listed in Figure 9 to Figure 11. The value was then divided by the age under curing exposure time, 14-day, 28-day and 56-day. Among all the mixtures, NC1, NC2 and NFA1, NFA2, for 14-day compressive strength achieved no maximum strength, then rises in the 28-day and 56-day. In 14-day NC1 shows lesser 27% compressive strength than NC2 and gradually increasing in 28-day and 56-day with a point 30% and 32%. The NC2 presents a good agreement with the portion of W/C 0.30 which is smaller than NC1 with 0.47. The same behaviour is also illustrated by FA1 and FA2 but informing the lower performance than NC1 and NC2. The FA1 compares to FA2 deponently increase by the 14-age, 28-age and 56-age in about 25%, 28% and 29%, respectively.

PC normally achieves its maximum strength in 28-day and increase insignificantly. However, FA imply a bit different than PC. FA increases gradually when the age of the concrete increasing. The greater portion of FA also gives the pattern of the performance including the class type of FA. In fact, this portion of the mixture using 30% replacement of cement still give a good result according to design specification. It is proved by composition of NFA in both W/C. NFA follow the raising of compressive strength when the age of curing increasing. These NFA considers effect FA on water demand of concrete proportioned for equal slump. In addition, NC2 and NFA2 in the age of 28-day inform higher compressive strength, 30% and 28%, respectively. Another indication from the comparison of NC2 and NFA2 were also in good agreement that the use of FA decrease the compressive strength around 3% to 6%.

Table 4 informs the variety of modulus of rupture and modulus of elasticity of concrete specimens which are classified in two different W/C ratios. Results shows that as far as the compressive strength is concerned in both NC and NFA, regardless of W/C, produced concrete with an acceptable ultimate compressive strength, $f'_c$. However, $f'_c$ decreases as the W/C increased. Results also indicate that modulus of fracture, $f_c$ and modulus of elasticity, $E_c$ for concrete made by PC is always higher that the corresponding FA. This observation agrees the findings of another research conducted by Alfian [20]. This condition may be attributed to the composition of W/C.

As the information given from Table 4, the compressive strength is customarily used to understand many of the engineering properties of the concrete which have concerned in a good performance such as $f_c$ and $E_c$. Measured values of $f_c$ of NC and NFA is accordingly to Table 4 which is divided by the effect of the ages. The result concedes with the $f'_c$ to $f_c$. The evaluation of $f_c$ and $E_c$ is according to ACI formula [21].

| Type of Mixture | W/C | Strength (Mpa) | Modulus of rupture (Mpa) | Elasticity (Gpa) |
|----------------|-----|----------------|-------------------------|-----------------|
|                |     | 14-day | 28-day | 56-day | 14-day | 28-day | 56-day | 14-day | 28-day | 56-day |
| NC1 0.47       |     | 24.86  | 27.29  | 28.37  | 3.49   | 3.66   | 3.73   | 23434  | 24553  | 25034  |
|                |     | 24.24  | 26.9   | 27.97  | 3.45   | 3.63   | 3.70   | 23140  | 24377  | 24857  |
| NC2 0.3        |     | 28.48  | 31.94  | 32.28  | 3.74   | 3.96   | 3.98   | 25082  | 26562  | 26703  |
| NFA1 0.47      |     | 23.16  | 26.44  | 27.24  | 3.37   | 3.60   | 3.65   | 22619  | 24167  | 24530  |
|                |     | 23.27  | 25.88  | 27.07  | 3.38   | 3.56   | 3.64   | 22672  | 23910  | 24454  |
|                |     | 27.24  | 30.58  | 31.77  | 3.65   | 3.87   | 3.95   | 24530  | 25991  | 26491  |
| NFA2 0.3       |     | 28.09  | 30.92  | 32.45  | 3.71   | 3.87   | 3.99   | 24910  | 25965  | 26774  |
|                |     | 25.75  | 28.99  | 30.41  | 3.55   | 3.77   | 3.86   | 23850  | 25306  | 25918  |
|                |     | 26.22  | 29.16  | 30.01  | 3.58   | 3.78   | 3.83   | 24067  | 25380  | 25747  |
|                |     | 25.88  | 29.39  | 29.9   | 3.56   | 3.79   | 3.83   | 23910  | 25480  | 25700  |
\[ f_r = 0.7 (f'_c)^{0.5} \]  

(1)

\[ E_c = 4700 (f'_c)^{0.5} \]  

(2)

The comparison for both NC and NFA is similarly presented the same and also well-informed in Table 4. The tendency of the result is small but comparable to each mixture proportioned. In general, the empirical relationship of the Eq. 1 and Eq. 2 have the benefits in simplicity, for the exact evaluation, experimental program has to be handed.

4. Conclusions
Based on the result conducted on variety of compressive strength age stage vs the water-to-cement ratios using FA class C as a replacement, the following conclusions can be drawn:

1) The rate gaining in strength of FA with variety of 0.47 and 0.30 W/C are observed to be lower than the corresponding PC concrete.

2) FA provides a satisfactory result concerned the high-volume replacement as 30% which is nearly reached the same capacity as PC concrete.

3) FA with a low calcium content with 30% replacement shows no optimum strength and implies a similar behaviour with NC.

4) Modulus of fracture and modulus elasticity for both NC and NFA is comparable to the compressive strength which illustrates the similar behaviour.

5) The application of FA using high-volume mixture as a replacement of cement reduces CO\textsubscript{2} emission that impact to the safety environment and energy conservation.

5. References
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