Mechanical properties of self-compacting concrete incorporated with high volume fly ash

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Abstract. Self-compacting concrete (SCC) is beneficial in concrete casting process as it does not need any tools for consolidation process. In addition, the utilization of High content fly ash in has proven in improving mechanical properties of concrete although the slow strength development is an issue to cope with. This paper presented an experimental program on the mechanical properties test of high strength self-compacting concrete incorporated with high content fly ash. The mix proportion for the concrete was prepared based on ACI high strength concrete with the design strength of 45 MPa. The mechanical properties test consists of slump flow test, compressive strength test development, flexural strength test and water absorption test of concrete. The slump flow test was tested for fresh concrete and the strength development test was tested at the age of 14, 28 and 56 days. In addition, test for flexural strength specimen and absorption specimens were tested at the curing age of 56 days. Moreover, the high strength normal concrete specimen was prepared as control mix design. The result shows, less water was need to reach design flowability for Self-Compacting Concrete High content fly ash concrete and it gives impact to lower water absorption for the type of concrete. In addition, at the curing age of 56 days the compressive strength of high strength high content fly ash-self compacting concrete was comparable to the normal concrete.

1. Introduction
Concrete is globally used construction material to support modern infrastructure. The dramatic increase of modern infrastructure such as skyscraper building needs more reinforcement inside reinforced concrete as element of structure, i.e.: column, beam and shear wall. It leads to narrow spacing of reinforcement and increase the difficulties in compaction of fresh concrete inside the formwork. Therefore, the use of self-compaction concrete become a perfect solution to produce dense, strong and durable concrete.

Self-Compacting Concrete (SCC), was developed for the first time by Japanese researchers in the late 1980’s. It is an extremely workable concrete that can flow under its own weight through narrow sections without segregation and bleeding [1]. SCC does not need any vibration equipment in compaction process and its high flowability makes the fresh concrete can easily fill up its formwork to reach its optimum dense. The fresh Self-Compacting Concrete generally have a relatively low yield value to ensure high flowability, a modest viscosity to avoid segregation and bleeding, and should keep its homogeneity during transportation stage, pouring and curing process to ensure the hardened concrete meet with structural performance and long-term durability. The successful casting of Self-Compacting Concrete must guarantee a perfect balance between deformability and stability. Mix
proportion of SCC always introduce superplasticizer to produce high flowability of fresh concrete and may use appropriate pozzolanic material, such as fly ash, rice husk ash, silica fume, and slag.

Fly ash is the most widely accepted pozzolanic material in concrete, which is a by-product of combustion of ground or powdered coal exhaust fumes in coal-fired power station [2]. The burning process uses burning temperature of 1,300 – 1,400°C. The fly ash is removed from the dust collection system of the exhaust gasses in coal fired power stations before they are discharge in to the atmosphere, as very fine particles, predominantly spherical glassy. The fly ash size of particle ranges from 1 – 150 µm which is generally finer than particle size of Portland cement. In addition, the size of particles is close related to the type of dust collection equipment [3].

There are three major chemical substance in fly ash i.e. Silica (SiO$_2$) around 5-25%, Alumina (Al$_2$O$_3$) about 10-30%, and ferric oxide (Fe$_2$O$_3$) about 5-25%. In addition, the other chemical substance in fly ash are calcium oxide (CaO), magnesium oxide (MgO), Sulphur trioxide (SO$_3$) and alkali oxide (Na$_2$O)$^2$. According to the major chemical contents, type of fly ash can be devided into three i.e. class F, class N, and class C fly ash.

The utilization of fly ash as a binder has demonstrated in improving many concrete properties, both in hardened concrete and fresh concrete [4]. The use of fly ash as partially cement replacement make improvement in fresh concrete for increasing the workability, reducing bleeding, and retarding time set. In addition, for hardened concrete, fly ash contributes in continuing the hardened concrete’s pozzolanic activity to gain higher strength for longer period, while the strength contribution rate of Portland cement decreases. Moreover, the most contribution of fly ash in hardened concrete is significantly improve the durability performance [2].

Previous researcher shows the utilization of high content fly ash as partial cement replacement produce a comparable compressive strength in comparison to normal concrete. Despite of its benefit the utilization leads to the slow strength development because fly ash needs Ca(OH)$_2$ a product of cement hydration. As high content fly ash concrete used minimum 50% of fly ash cement replacement, the replacement is beneficially to the environment to reduce significantly the CO$_2$ emission from cement production.

Based on the discussion this paper will explore the utilization of high content fly ash concrete to produce self-compacting concrete. The discussion in this paper will focus on some properties of self-compacting concrete for fresh concrete (slump flow test) and for hardened concrete (compressive strength, flexural strength and water absorption).

2. Research method
The research programs consist of 5 stages i.e.: material and equipment preparation, concrete specimen casting, curing of the specimens, test of the specimens and analysis and discussion. Material for concrete specimens was selected from local quarry in Surakarta region which is meet the standard as concrete material. Following the material preparation, a 45 MPa mix proportion of concrete was prepared based on ACI mix proportion for high strength concrete and the following table (Table 1) shows the mix proportion.

|                   | SCC normal concrete | SCC HVFA concrete |
|-------------------|--------------------|-------------------|
| Cement (kg/m$^3$) | 527.0              | 263.5             |
| Fly ash (kg/m$^3$)| 0                  | 263.5             |
| Fine Aggregate (kg/m$^3$) | 878.0       | 878.0             |
| Coarse Aggregate (kg/m$^3$) | 756.0       | 756.0             |
| Water (kg/m$^3$)  | Design: 190.0     | Design: 190.0     |
| SP (kg)           | Actual: 180.0     | Actual: 155.8     |
|                   | 7.9                | 7.9               |
There are two type of mix design in this experimental work i.e.: high strength self-compacting concrete normal concrete and high content fly ash in. For normal concrete all of binder is Pozzolanic Portland cement (PPC) produce from Portland Cement factory whereas for HVFA concrete half of PPC was replaced by fly ash type F.

In preparation of self-compacting concrete mix proportion, some considerations were taken, i.e.: maximum size of aggregate was 10 mm and the total weight of fine aggregate was higher rather than total weight of coarse aggregate. In addition, 7.9 kg/m³ superplasticizer type: viscocrete-10 was used to improve flowability of SCC. Although the w/c ratio was designed at 0.36 the actual water used was maintained at minimum amount to reach workability design. It leads to lower water usage rather than the designed w/c ratio.

The lower water usage for HVFA concrete in comparison to normal concrete shows that the utilization of fly ash increases the workability of concrete. The increase of workability is possibly caused by the spherical shapes of the fly ash that reduces the friction between cement and aggregates and results in an increase in the workability of fresh concrete [5]. Previous researcher also reported the higher slump test for high content fly ash was caused by the increase of concrete workability and it is close related to the spherical fly ash particle [6-8].

The specimens for testing consist of cube 15 x 15 x 15 cm for compressive strength test, small beam 15 x 15 x 50 cm for flexural strength test and cylinder diameter 10 x 5 cm height for water absorption test. After 24 hours of casting process the specimens were removed from mold and the curing process is started by immersing them in water until one day of testing date. The number of specimens and the design test date is shown in Table 2.

| No | Testing program   | Specimen                   | Specimen’s age (days) |
|----|-------------------|----------------------------|-----------------------|
| 1  | Compressive strength | Cube 15 x 15 x 15 cm  | 8  8  8               |
| 2  | Flexural strength  | beam 15 x 15 x 50 cm      | 6                     |
| 3  | Water absorption  | cylinder dia. 10 x 5 cm height | 6 |

The matrix of specimen table shows, there are 4 compressive strength specimens for each type of mix design and for different curing age. However, there are 3 flexural strength test and 3 water absorption test for each type of mix design. The total number specimens need to be prepared was 36.

3. Result and discussion
The result and discussion of High Strength Self Compacting Concrete High content fly ash concrete starting with the investigation of material to be used in casting the concrete specimen. The investigation on fine aggregate and coarse aggregate shows that all of them meet the standard requirement of SNI as concrete aggregate. Therefore, they can be used to cast the concrete and the experiment can be carried on. The next examination is exploring chemical substances in fly ash. The fly ash used in the research was a by-product of power plant combustion in Java Island and collected from PT. Jaya Ready Mix Sukoharjo. The chemical test was conducted at Laboratorium Pengujian dan Kalibrasi BARISTAND INDUSTRI Surabaya and the following table shows the chemical content of fly ash.

| No | Chemical composition | Percentage % | ASTM Standard          |
|----|----------------------|--------------|------------------------|
| 1  | SiO₂                 | 86.09        | SiO₂ + Al₂O₃ + Fe₂O₃   |
| 2  | FeO₃                 | 1.64         | min. 50%               |
| 3  | Al₂O₃                | 5.97         |                        |
| 4  | CaO                  | 2.31         |                        |
| 5  | MgO                  | 0.45         |                        |
| 6  | Loss of Ignition     | 2.16         |                        |
The data in Table 3 shows that the content of (SiO₂ + Fe₂O₃ + Al₂O₃) is 93.60%, while the minimum standard of those three major components for fly ash class C is 50%, and the standard of those for Fly ash class F is 70%. Hence, it can be concluded that fly ash from PT. Jaya Ready Mix Sukoharjo belongs to Fly ash class F (ACI Manual of Concrete Practice 1993) [9].

3.1. Slump flow test.
Slump flow test is design to check the flowability of fresh concrete to ensure that the fresh concrete can fill up the formwork to achieve maximum dense. The test carried on by measuring the diameter of fresh concrete on a flat surface after removing from slump cone. The test and the result are shown in Figure 1 and Table 4.

![Figure 1. Diameter measurement of slump flow test][10]

Table 4. Slump flow test result

| Kode         | Diameter 1 (mm) | Diameter 2 (mm) | Average (mm) |
|--------------|-----------------|-----------------|--------------|
| SCC normal   | 580             | 620             | 600          |
| SCC HVFA     | 595             | 605             | 600          |

The diameter of slump flow test result is 600 mm for SCC normal concrete and also for Self-Compacting Concrete High content fly ash concrete. As the requirement of diameter in slump flow test for SCC is 500 – 700 mm, therefore both mix proportion meet the criteria of SCC. In addition, the less water used in HFVA concrete was not reduce the flowability of fresh concrete. This fact shows that the use of HVFA as partial cement replacement increase the workability of fresh concrete due to the spherical shape of fly ash.

3.2. Compressive strength test.
Compressive strength test was conducted at the age of 14 days, 28 days and 56 days to determine the strength development. The test was conducted on 15 x 15 x 15 cm³ concrete cube and the specimen was prepared by taken out from the curing tank one day before the day of test. As shown in Figure 2 the load was applied on the cube until maximum load and the following formula is used to find out the compressive strength [11].

\[ f'_c = \frac{P}{A} \]

where:
- \( f'_c \) = Compressive strength (MPa)
- \( P \) = Maximum load (N)
- \( A \) = surface area of cube (mm²)
Figure 2. Compressive strength test of SCC

As the compressive strength was carried on 15 x 15 x 15 cm cube, it needs 0.83 correction factor to convert the compressive strength to cylinder diameter 15 cm and 30 cm height. Based on compressive strength test result at Figure 3, at early age i.e.: 14 days and 28 days the compressive strength of Self-Compacting Concrete of normal concrete relatively higher than the Self Compacting Concrete High content fly ash concrete. However, at the age of 56 days, differently from Self Compacting Concrete High content fly ash that continuously improve the compressive strength development, the SCC normal concrete did not improve the compressive strength. This result shows a slow strength development of fly ash concrete.

Figure 3. Compressive strength result of SCC

The slow development of concrete compressive strength is possibly caused by the low cement used in high content fly ash, so that the concrete has low C₃A content from cement, the substance which mainly contributes for early age strength. Previous researcher confirmed that phenomena that fly ash concrete usually demonstrates lower strength at early ages especially for high content fly ash concrete in comparison to ordinary portland cement (OPC) concrete, although it shows higher strength at a longer period of time [12, 13].

3.3. Flexural strength test.

The flexural strength was tested on concrete beam with the dimension of 15 x 15 x 50 cm under one-point load (Figure 4). The test was conducted after 56 days of curing age to ensure Self Compacting Concrete High content fly ash concrete reach the comparable strength to normal concrete. The flexural strength test is calculated by using this formula:
Where

\[ f_{it} = \frac{3P}{2bd^2} \]  

(2)

\( f_{it} \) = Flexural strength (MPa)

\( P \) = Maximum load (N)

\( L \) = Clear span (mm)

\( b \) = average width of beam (mm)

\( d \) = average height of beam (mm)

The flexural strength test result in Figure 5 shows at the age of 56 days the SCC normal concrete had higher flexural strength in comparison to Self-Compacting Concrete High content fly ash concrete. It is noted in here that HVFA concrete probably more brittle rather than normal concrete. The lower modulus of rupture for fly ash in comparison to normal concrete was also reported by Duran-Herrera et al [14].

![Center-point Loading](image)

**Figure 4.** Test set up for flexural strength

![Flexural strength test result of SCC](image)

**Figure 5.** Flexural strength test result of SCC

### 3.4. Water absorption test.

Water absorption test is aimed to test the amount of water can be absorbed by the concrete and this property closely relate to the concrete durability properties. The test was conducted by finding the differences of water content between saturated specimen and oven dried specimen with diameter 10 cm and 5 cm height. There are two types of absorption tested, i.e. saturated water absorption and immersed water absorption. Saturated absorption measures the total absorption of water when the specimen is in saturated state while Immersed absorption measures the total water that can be absorbed by the concrete after soaking the specimens in water for two days.
This research focus on saturated water absorption and for saturating process of the specimens, the method in ASTM standard of preparing a concrete specimen for rapid chloride penetration testing method was used [15]. The procedure of testing was started by vacuuming the sample to suck up all the entrapped air in concrete voids for three hours following by soaking it into water for 18 hours. The following equation is used to calculate the water absorption of concrete:

\[
\text{Water absorption} = \frac{W_1 - W_2}{W_1} \times 100\%
\]  

Where:
- \(W_1\) = Oven dried specimen (gram)
- \(W_2\) = Saturated weight of specimen (gram)

The result of water absorption in Figure 6 at concrete age of 56 days shows the significant decrease of water absorption in HVFA concrete in comparison to normal concrete. The lower the durability in concrete will be beneficial in improving durability of concrete.

![Figure 6. Water absorption test result of SCC](image)

The possible factors affect to lower water absorption of fly ash concrete is the permeability of the transition zone surrounding the aggregate and also the permeability of the cement paste as reported by Haque and Kayali [16]. Moreover, High content fly ash concrete system has discontinuation of pore structure that is also contributes to the lower water absorption [17].

4. Conclusion
Based on the results of the analysis High Strength Self-Compacting Concrete High content fly ash concrete, the research has drawn some conclusions. First, self-compacting concrete with high content fly ash concrete has similar flowability as self-compacting normal concrete, and even better as HVFA concrete needs less water to reach design flowability. Second, the compressive strength of HVFA concrete is better than normal concrete especially after longer period. Third, as flexural strength of HVFA concrete is lower rather than normal, it indicates that HVFA concrete more brittle than normal concrete. Fourth, water absorption of Self-Compacting Concrete High content fly ash concrete is lower rather than SCC normal concrete which is indicate superior Durability properties. Further research needs to be conducted to explore the effect of using fly ash more than 50% to produce high strength high content fly ash Self Compacting Concrete.
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