Concrete Performance with Ground Granulated Blast Furnace Slag as Supplementary Cementitious Materials

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Abstract. Supplementary Cementitious Materials (SCMs) are materials that contribute to the hardened concrete properties through hydraulic or pozzolanic activities. The use of Ground Granulated Blast Furnace Slag (GGBFS) as SCMs or partial replacement of cementitious components in concrete provides benefits both in terms of economy and performance improvement. However, GGBFS is not widely known in Indonesia, hence the available research for this product is still limited. In this study, the performance of concrete with GGBFS as a partial replacement for cement was investigated, with the percentage of GGBFS varying by 0%, 30%, 50% and 70% of cement weight. The mechanical properties of concrete being observed are compressive strength and elastic modulus. Porosity testing is carried out to assess the durability aspect of concrete. Compressive tests are carried out when the concrete age reached 7, 28, 56 and 90 days to assess the strength development of GGBFS based concrete. From the study, it was found that GGBFS can replace cement up to a percentage of 50%, with its compressive strength comparable to conventional concrete. However, the addition of GGBFS in concrete mixes slowed the development of concrete compressive strength at early age. Concrete modulus of elasticity decreases with increasing GGBFS, but not significantly. The increasing percentage of GGBFS causes the pore volume to decrease, indicating the greater durability of GGBFS based concrete compared with the conventional one.

1. Introduction

Concrete is one of the most widely used construction materials in the world, including in Indonesia. The widely use of concrete is due to its high strength, versatility, durability, and other benefits in terms of low production, transportation and installation costs. However, the production of cement as binding material in concrete has a considerable environmental impact. Until 2014, world production of cement has reached 4 billion tons, which accounted for 8% of total CO₂ gas emissions. Half of the gas emissions are the result of combustion of fossil fuels, while the other half is due to calcination of limestone [1].

Cement as binding material in concrete still cannot be completely replaced by other materials. However, there have been many studies on the partial replacement of cement with pozzolanic materials, such as: fly ash, silica fume, rice hull ash and, the recently developed material in Indonesia, granulated blast furnace slag or GGBFS. Ground granulated blast furnace slag (GGBFS) is obtained from an iron slag, a by-product from the manufacture of iron and steel. The liquid iron slag from the blast furnace is rapidly quenched using water to obtain granular products, which are then dried and mashed to form a powder (very fine grain). With advanced processing technology, the iron and steel industry waste is transformed into an economical cementitious material that has the potential as a sustainable material for concrete mixes.
Many studies of the effect of using GGBFS as cement partial replacement on both concrete properties and characteristics has been conducted. Previous studies shows that by adding GGBFS on concrete mixes, the overall concrete performance was improved, includes: strength, workability, permeability and durability. Research conducted by Wang, et al. [2] and Turu’allo [3] found that concrete with GGBFS had better workability than concrete with ordinary Portland cement or OPC, where the fluidity of the paste is increased. Further studies by Turu’allo [3], Rughooputh, et al. [4] and Raman and Krishnan [5] proves that GGBFS can be used as a sustainable cement replacement material, shown by concrete compressive strength that continues to increase until replacement level of 40% - 50% GGBFS to the weight of cement.

Despite its high potential sustainable partial cement replacement, GGBFS itself is not widely known in Indonesia. The fact is, GGBFS was recently introduced in 2018 with the launch of the product by PT. Krakatau Semen Indonesia. The available research for this new product is still limited, either of GGBFS effect as partial cement replacement on hardened concrete properties, or how high the percentage of cement can be replaced with. In this study, the change in mechanical properties of concrete with the various replacement levels of GGBFS was investigated, which includes compressive strength and its development relative with concrete ages and the stress-strain curve up to peak strength. The workability of the fresh concrete with GGBFS was also studied. The porosity of concrete with GGBFS was investigated to know its durability aspect.

2. Experimental Procedure
2.1. Experiment Materials and Specimen Preparations
The materials used in the concrete mixes was consist of Portland Cement, GGBFS, coarse aggregate and fine aggregate. The coarse aggregate was crushed stone with a diameter within 5 – 30 mm; the fine aggregate was natural sand river with a diameter of 0 – 5mm. Ordinary Portland Cement and ground granulated blast furnace slag from PT. Krakatau Semen Indonesia was used as binder. The cement was replaced with four different replacement levels of GGBFS, which was 0%, 30%, 50% and 70% by weight of cement. The water – binder ration was at a constant value of 0.45. The material proportion for the concrete mixes was shown in table 1. There was no addition of chemical admixture in the concrete mixes.

The size for concrete cylinder specimens were 150 x 300 mm, which was used for determines the concrete compressive strength as well as the stress-strain curve up to the peak strength. Cubic concrete specimens were 100 x 100 x 100 mm, and designated to test the porosity of the concrete. All of the specimens were cast in steel molds. After 24 hours, the specimens were demolded and cured for 7, 28, 56 and 90 days.

| Specimen | GGBFS% | Water (kg/m³) | Binder (kg/m³) | Aggregate (kg/m³) | Sand (kg/m³) | w/b |
|----------|--------|---------------|----------------|-------------------|-------------|-----|
| SN       | 0      | 194           | 428            | 0                 | 815         | 996 | 0.45 |
| SG30     | 30     | 194           | 300            | 128               | 815         | 996 | 0.45 |
| SG50     | 50     | 194           | 214            | 214               | 815         | 996 | 0.45 |
| SG70     | 70     | 194           | 128            | 300               | 815         | 996 | 0.45 |

2.2. Uniaxial Compressive Strength Test
The average compressive strength of three specimens per batch was measured according to SNI 1974:2011 method. The compressive strength was taken right before peak load begins to decrease. Concrete cylinders were tested at 7, 28, 56 and 90 days to determine the strength development of the concrete specimens.

2.3. Determination of Stress-strain Curve
The stress-strain curve of concrete was taken up to the peak strength. This curve was used to
determine elastic modulus of the concrete, as well as the concrete strain at the peak strength. The test
was conducted manually. Strain of the concrete specimen was measured using compressometer with
digital gauge. Each strain increase was recorded, then the stress was computed for observed strain.
Modulus of elasticity was determined as the ratio between concrete stresses at 40% of its peak strength
and its corresponding strain. This test was carried out when concrete age reach 28 days.

2.4. Porosity Test
Volume of permeable voids of concrete specimens was measured using ASTM C642 testing standards.
Porosity test using cubic concrete specimens was carried out when the concrete age was 7, 28 and 56
days. First, the specimen was dried in an oven at 100°C for 48 hours. Then, the specimens were
cooled to room temperature and being measured for its weight. Saturation of the specimen is done by
boiling the specimen for 5 hours. Tests were carried out for each GGBFS replacement levels.

3. Result and Analysis
3.1. Strength Development of Concrete
Concrete compressive strength was measured when the concrete age reached 7, 28, 56 and 90 days. At
the age of 7 days, control mixture (SN) has a higher compressive strength than concrete containing
30%, 50% and 70% GGBFS (SG30, SG50 and SG70). The use of GGBFS as a partial replacement
material for cement causes a decrease in compressive strength at early age, but the strength of concrete
increases afterwards at later age (Figure 6).

At the age of 28 days, the compressive strength of concrete mix with 30% GGBFS (SG30) and
50% GGBFS (SG50) increased to almost equivalent to control mixture (SN), but it was still slightly
deeper. Concrete compressive strength containing 30% and 50% GGBFS content was respectively
2.7% and 3.8% lower than the control mixture (33.8 MPa). Concrete compressive strength was
decreased further at 70% GGBFS content, which has 19.3% loss as compared to the control. Similar
results were also reported by Łukowski [6]. Compressive strength test of mortar at 28 days conducted
by Łukowski [6] showed a loss in strength of 4.6%; 10.3%; and 23.0% compared to control mixture
(43 MPa) at GGBFS levels of 30%, 50% and 70%, respectively.

At 56 days, the compressive strength of concrete containing 30% and 50% GGBFS has exceeded
the 28-day compressive strength of the control mixture. Compressive strength of concrete with 30%
and 50% GGBFS content continue to increase till it exceeded the control mixture strength at 90 days.

3.2. Concrete Stress-strain Curve
It is evident from the result that in increasing GGBFS content, the strain at peak value increases
(Figure 2). This indicates that concrete will fail at a higher rate of strain which also means greater
durability. Similar findings was also observed by Das et.al. [7]. Das et.al. replaced partial of fine
aggregate with ground granulated blast furnace slag and noticed that the rate of strain increases with
the increasing of GGBFS percentage.
Figure 1. Development of concrete compressive strength with various replacement of GGBFS relative with age

Figure 2. Relationship between stress and strain up to peak strength

Table 2. Modulus of elasticity of concrete specimens.

| Specimen | Modulus of Elasticity @0.4 f_c (GPa) |
|----------|-------------------------------------|
| SN       | 19.05                               |
| SG30     | 17.61                               |
| SG50     | 16.03                               |

In this study, the modulus of elasticity is calculated at 40% of the peak stress. The results showed that the modulus of elasticity of the concrete decreased slightly due to the addition of GGBFS in the concrete mixture (Table 3). This can actually be seen from Figure 2 where the slope from 0 to 40% of peak strength was gradually becoming less steep, indicates a lower value of modulus of elasticity. Siddique and Kaur [8] observed similar findings wherein they reported 22.5%, 39.98% and 41.7% loss in modulus of elasticity as compared of the control (15.98 GPa) at 20%, 40% and 60% GGBFS content, respectively.

3.3. Concrete Porosity
Figure 3 shows the variation in volume of permeable voids in concrete with various levels of GGBFS replacement. It was shown that the voids or pore volume in concrete specimens tends to decrease along with the increases of GGBFS percentage, especially when concrete age is 28 and 56 days, where the hydration process has reduced the pores in the concrete matrix. The reduction of permeable voids
in concrete means greater concrete resistance against chemical attack, when concrete is exposed to extreme environmental conditions.

Changes in the structure of the cement paste matrix due to the addition of GGBFS were also reported by Łukowski [6]. Mortars with GGBFS have better resistance to chemical attack due to the denser structure of cement paste. Research by Akram and Raza [9] also proves that the addition of GGBFS in a concrete mixture can reduce concrete permeability, with the value of concrete permeability getting smaller with increasing levels of GGBFS.

3.4. Workability of Fresh Concrete
From the results of slump test (Table 3), it was found that the concrete mixture with GGBFS has a higher slump, with the slump value increasing with increase in GGBFS content. Increased slump values due to the addition of GGBFS in concrete mixes were also reported by Turu’allo [3].

![Figure 3. Volume of permeable voids of concrete with various GGBFS replacement levels](image)

**Table 3. Slump of fresh concrete mix**

| Specimen | Slump (mm) |
|----------|------------|
| SN       | 17.50      |
| SG30     | 25.00      |
| SG50     | 37.50      |
| SG70     | 55.00      |

4. Conclusion
The effect of GGBFS as partial cement replacement on mechanical properties of concrete was investigated in this study. It was found that GGBFS can be used as partial replacement of cement up to 50% of cement weight without reducing the concrete compressive strength. However, concrete contained GGBFS has lower compressive strength at early age, so the usage of concrete with GGBFS is more suitable when high initial strength is not required. GGBFS based concrete will have slower strength development compared to conventional one, which might cause the strength to not be perfectly reached at 28 days. Incorporating GGBFS to the concrete mix could improve the fluidity of cement paste, resulting in better concrete workability. The usage of GGBFS as cement partial replacement has positive effect on the durability of concrete. The pore volume of concrete was reduced with the increase of GGBFS content, effectively raised the concrete resistance against chemical attacks. However, this result must still be verified, which is part of the next research plan.
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