Effect of using geopolymer flyash on torsion capacity of hybrid high-strength reinforced concrete beams containing fine and coarse aggregates substitution which added iron ores as filler

T B Aulia*, M Muttaqin, M Affuddin, M Zaki and G Nastiti

Syiah Kuala University, Banda Aceh 23111, Indonesia

*aulia@unsyiah.ac.id

Abstract. High demand for advanced infrastructure leads to the use of high-strength concrete. Complex, futuristic and asymmetrical building construction may create dangerous torsional load and moment, mainly due to earthquake. Using large amount of cement makes high-strength concrete not environmentally friendly. The use of natural aggregates continuously reduced its availability. Efforts to substitute cement and aggregate from abundant and environmentally-friendly natural materials could be smart solution. This study aims to analyze the torsional capacity of high-strength cantilever reinforced concrete beams having L configuration with a torque arm. Three hybrid beams were cast with substitution of 15% coal flyash (CFA), 15% palm oil blast furnace slag (POSFA) and 10% pozzolanic flyash (PFA) from cement weight, added with 10% pozzolanic sand as fine aggregate substitution and 40% palm oil blast furnace slag as coarse aggregate substitution. One beam without flyash and aggregate substitution (NPBHSC) was tested as comparison. All four beams added with iron ore as filler. The best torsion capacity achieved by PFA beam with maximum load (P) 2.83 ton, maximum torsion moment (M) 10.4 kNm, maximum torsion angle (θ) 0.0225 rad, ductility (µ) 3.941 and cylinder compressive strength (σ) 59.48 MPa, when compared to NPBHSC beam which produced P = 2.65 ton, M = 9.638 kNm, θ = 0.0069 rad, µ = 1.008 and σ = 44.40 MPa. POSFA beam followed then by CFA resulted in slightly smaller P and M, but generated greater σ, θ and µ than NPBHSC. It can be concluded that geopolymer flyash can increase compressive strength, torsion capacity and ductility of high-strength reinforced concrete beams.

1. Introduction

Production of high-strength concretes needs a large amount of cement, best quality aggregates and additives and superplasticizer causing high production costs. On the other hand, high-strength concretes provide some superiorities in term of strength, stiffness, durability, service life and efficiency in comparison with normal-strength concretes, so that it is suitable for advanced and innovative infrastructures such as high-rise buildings, bridges with long spans, large dams, airports, deep foundations [1,2]. However, the use of large amount of cement makes high-strength concretes not environmentally friendly. Cement production at the factory requires a lot of calcium based raw materials in form of limestone and clay heated with high temperature up to 1500 °C and even more to obtain active and refined clinker. As a consequence, the process leads to wasteful of fuel and consumes plentiful natural resources. Process of cement manufacturing also become the biggest contributor to the CO₂ emissions.
emission to the atmosphere, in which 1 ton CO$_2$ will be released to the atmosphere by production of 1 ton Portland cement, generating greenhouse effect as a trigger of global warming which has happened in the past decades [1-3].

Aggregates occupy a volume of 60-75% of the concrete matrix volume which is mostly mined from natural sources. Nevertheless, the availability of aggregates originating from rivers and natural rocks reduces from year to year due to continuous exploitation for concrete production and other uses. Therefore, efforts to substitute cement and aggregates in producing high-strength concretes from environmentally-friendly natural and waste materials, which are available abundantly in nature could be a smart solution to achieve green construction and cost-effective infrastructures. Potential solution for this problem is the use of natural geopolymer flyash i.e., coal flyash, pozzolanic flyash and palm oil blast furnace slag ash as supplementary cementing materials for cement replacement; and pozzolanic sand as fine aggregate substitution; as well as industrial waste palm oil blast furnace slag as coarse aggregate substitution [1]. Through the use of these materials it is expected that they could still provide the good mechanical properties and durability same as the fully cement based high-strength concretes.

In accordance with Indonesia's geographical conditions which are among the encountering of three very active tectonic plates, namely the Indo-Australian oceanic plate in the South, the Eurasian continental plate on the North and the Pacific oceanic plate on the East, aggravated by the faults on the big islands, making the territory of Indonesia is very vulnerable to earthquake disasters. Nowadays, more and more buildings with modern, futuristic and asymmetrical designs are built, which although aesthetically look beautiful, but asymmetrical buildings have a center of mass and a center of rigidity that do not coincide resulting in eccentricity. Eccentricity can cause twisting when the building structure receives earthquake lateral loads. When the developed moment exceeds the torsional capacity, the building could fail. Another case where torsion is significant is in the arch bridge, spiral staircase, balcony girder, and anywhere bearing a large load that works not at the "mass center" of the beam. It should be realized that if the support rod can rotate, the resulting torsional stress will be small. But if the rod is restrained, the twisting stress will be very large.

Coal flyash is the coal burning waste having more finer grain than Portland cement collected from electric steam power plant. According to SNI 2460-2014 [4], coal flyash could be divided into three types, i.e., raw natural pozzolan or calcined ones conforming with the applicable requirements (Class N); pozzolan which is produced by burning anthracite coal or bitumen (Class F); and pozzolan which is produced by burning lignite coal or subbitumen (Class C). Flyash class C contains calcium oxide which is higher than that of class F. Natural pozzolan is another geopolymer additive, which is sedimentation material from volcanic ash containing silica alumina compound in an amorphous form. In concrete mix, it will react with Ca(OH)$_2$ released in the primary hydration process to form extra Calcium Silicate Hydrate (C-S-H) compound resulting in an increase in concrete strength. Palm oil blast furnace slag is solid waste resulting from combustion of bunches, fibers and shells of crude palm having pozzolanic characteristics because of the high silica content. Indonesia has quite a lot of crude palm availability. In 2014 there were 10.9 million hectare of crude palm plantation producing crude palm oil of 29.3 million tons, resulting in 60% palm waste. Burning of crude palm waste at high temperature generates hard slag known as palm oil blast furnace slag containing high SiO$_2$ content. Such biomass is therefore potential to be used as additive flyash and aggregates in concrete [1].

The use of geopolymer materials, i.e., coal flyash, pozzolanic flyash, as well as waste material palm oil blast furnace slag as cement substitution and aggregates substitution on investigation of the flexural capacity of high-strength reinforced concrete (HSRC) beams has been carried out by Aulia et al [1]. The results showed that the used materials could increase bending capacity of the beams significantly. Further, Aulia et al. have investigated the shear capacity of HSRC beams using such geopolymer and waste materials with the same composition and concluded that palm oil blast furnace slag used as aggregate substitution could enhance the beam shear capacity but this tendency did not occur by using geopolymer flyash for cement replacement even though showing higher compressive strength compared with the plain beam [3]. Brittle behavior of the beam containing geopolymer flyash contributed for this finding.
Effect of geometry and configuration of transverse reinforcement in reinforced concrete beams has been investigated by Chalioris and Karayannis [5]. The results significantly showed that using rectangular spiral reinforcement could increase torsional capacity and enhance post-peak performance of the beams. Almost the same findings were also reported by Katkhuda [6] through his investigation on the torsional behavior of reinforced concrete beams. The results showed that application of continuous rectangular spiral reinforcement could improve torsional capacity 17% higher than using ordinary transverse reinforcements.

Study of torsional capacity and behavior of reinforced concrete beams regarding minimum reinforcement ratio; strengthening of reinforced concrete beams using aramid fiber strips; strengthening of reinforced concrete beams with sand-coated glass FRP (GFRP), carbon-FRP (CFRP) bars and stirrups has been revealed in [7-9]. An approach method for calculating the cracking moment of HSRC beams subjected to pure torsion has been recommended by M Husem et al. according to their research, which revealed the value that is closer to the experimental results in comparison with analytical calculations based on previous theories [10].

Nevertheless, all of the above cited torsion researches were carried out using built-in torsion test equipment integrated with computer. Torsion testing using modified reinforced concrete beam specimen, i.e., L-configured cantilever beam that given compressive load on its torsional arm has never been performed. Moreover, experiment about torsional capacity and behavior of HSRC beams using geopolymer flyash as cement replacement and filler, as well as waste material as aggregates substitution is still scruply investigated.

Therefore, this research aims to gain torsion capacity of hybrid HSRC beams containing geopolymer flyash namely coal flyash, pozzolanic flyash and palm oil blast furnace slag ash as cement replacement appended with pozzolanic sand as fine aggregate substitution and palm oil blast furnace slag as coarse aggregate substitution. The plain HSRC beam was cast as comparison. All beams added then with iron ore as filler. The main objective is to obtain the environmentally friendly, sustainable and cost-effective high-strength concretes with high torsional resistance.

2. Methods

2.1. Materials
Coal flyash utilized originating from electric steam power plant in Nagan Raya Regency, Aceh, possessing the content of chemical composition as follows: SiO$_2$ = 26.65%, Al$_2$O$_3$ = 9.6%, Fe$_2$O$_3$ = 17.56%, and SO$_3$ = 2.51% [1]. The amount of SiO$_2$, Al$_2$O$_3$, and Fe$_2$O$_3$ contents is 53.81% which according to ASTM C.618 is categorized into Class C flyash with a minimum SiO$_2$, Al$_2$O$_3$, and Fe$_2$O$_3$ content about 50% [11]. The pozzolanic flyash used in this research came from Beurandeh Village, Krueng Raya Subdistrict, Regency of Aceh Besar having chemical composition as follows: SiO$_2$ = 42.96%, Fe$_2$O$_3$ = 1.92%, CaO = 0.42%, MgO = 0.28%, Na$_2$O = 0.13%, K$_2$O = 0.36%, and TiO$_2$ = 0.12%. Its physical characteristics were 1.21 kg/l for the bulk density and 2.375 for fineness modulus [1]. In larger grain size, pozzolanic sand was used as fine aggregate substitution.

The used palm oil blast furnace slag had the content of chemical composition as follows: SiO$_2$ = 34.11%, Al$_2$O$_3$ = 3.57%, Fe$_2$O$_3$ = 2.06%, and SO$_2$ = 0.2% [1]. Iron ores are rock containing iron minerals and a number of other minerals such as silica, alumina, magnesia and nickel. The iron ores used came from Lhoong Subdistrict, Aceh Besar Regency, which had the following chemical content: Fe$_2$O$_3$ = 93.88wt%, SiO$_2$ = 3.43wt%, MnO = 0.55wt%, Al$_2$O$_3$ = 0.43wt% and several others [12].

As cement replacement, these flyashes were applied, i.e., coal flyash in amount of 15% which abbreviated as CFA, 15% palm oil blast furnace slag ash abbreviated as POSFA and 10% pozzolanic flyash abbreviated as PFA, each from cement weight, added then with 10% pozzolanic sand as fine aggregate substitution and 40% palm oil blast furnace slag as coarse aggregate substitution. HSRC beam without flyash and aggregate substitution was tested as comparison, abbreviated as NBHSC. Hereinafter, all beams were added with iron ores as filler in amount of 6% from cement weight. The substitution percentage was the optimum value from previous research.
HSRC beams with L configuration were cast with a w/c-ratio of 0.3 consisting of Portland cement type I in amount of 600 kg/m³ concrete and polycarboxylate ether based superplasticizer ViscoCrete-10 with a dosage of 1.5% from cement weight. Fine aggregate used was crushing stone with a maximum diameter of 4.76 mm and coarse aggregate was crushing stone with a maximum diameter of 12 mm.

2.2. Instrumentation and testing

HSRC beams with L configuration having a cross section 20x25 cm, the main beam length 80 cm and a torque arm of 40 cm, were reinforced with 4 D 14 mm for longitudinal reinforcement with $f_y = 350.50$ MPa and Ø 6 – 100 mm for torsional stirrups with $f_{st} = 381.65$ MPa, and $f'_c = 100$ MPa have been calculated to fail in torsion. Eight LVDTs were used to measure the twist angle and installed each 2 pieces on the top, bottom, left and right sides of the beam with a distance of 10 cm from the support. Four strain gauges were installed each 2 pieces at the stirrups (SG1 and SG2) and at the main reinforcement to measure the strain (SG3 and SG4).

Testing of torsional capacity of L-configured cantilever beams was carried out by giving a concentrated compressive load on its torsional arm through a hydraulic jack which connected then to the load cell. The load was run up for every 100 kg until the beams collapsed. Strain and deformation of the reinforced concrete beams were recorded utilizing portable data logger TDS-032. Specimens were tested at the age of 28 days with the observed parameter comprised the maximum torsion load, torsional moment and angle, structural ductility, stirrups and reinforcement strain and failure pattern of the beams. Crack pattern that occurred was visually observed and sketched on the surface of beam together with the given load. The specimen setup was showed in Figure 1 and Figure 2.

![Figure 1. Top View of Specimen](image1)

![Figure 2. Side View of Specimen](image2)

3. Results and discussion

3.1. Torsional moment and twist angle

The relationship between torsional moment and twist angle for all tested HSRC beams is exhibited in Figure 3. The beam with pozzolanic flyash (PFA) demonstrated the best torsional moment and twist angle relationship, which was followed then by HSRC beam containing coal flyash (CFA). In the beam comprising palm oil blast furnace slag (POSFA), even though the resistance moment was smaller than the plain beam (NBHSC), but generated a better deformation and twisting angle as shown particularly by PFA and CFA beams, which indicated a more ductile behaviour.
3.2. Load and strain of torsional stirrups

The relationship between load and deformation of torsional stirrups for all specimens was given in Figure 4 and Figure 5. The beams containing PFA and CFA produced small torsional deformation for both SG1 and SG2 compared to NBHSC. This means that HSRC beams substituted with pozzolanic flyash and coal flyash having a higher torsional resistance than NBHSC. In addition, the POSFA beam showed a better load and torsional deformation relationship than NBHSC, indicating a more ductile behavior, i.e., it can produce the same strain level but at a lower load, as shown in Figure 4. A similar torsional deformation behavior was also observed on the POSFA beam for SG2 (see Figure 5). In general, deformation at SG1 and SG2 occurred almost at the same level for each beams.

3.3. Load and strain of longitudinal reinforcement

The graphs of all load and deformation of longitudinal reinforcement were presented in Figure 6 and Figure 7. According to the graphs it could be observed that deformation of longitudinal reinforcement on the top right longitudinal reinforcement (SG3) was lower than that of on the bottom left longitudinal reinforcement (SG4). This occurred because the beam would twist counter-clockwise due to given torsional load. PFA beam resulted in lower torsional deformation for both SG3 and SG4 indicating a high torsional resistance.
3.4. Ductility

Table 1. Structural ductility of high-strength reinforced concrete beams.

| No. | Specimen | $\varepsilon_y$ | $P_y$ | $\theta_y$ | $\varepsilon_u$ | $P_u$ | $\theta_u$ | $\mu$ | Ratio to NBHSC |
|-----|----------|-----------------|------|----------|-----------------|------|----------|------|---------------|
| 1   | NBHSC    | 0.200           | 2.215 | 0.00258  | 2.477           | 2.070 | 0.00260  | 1.008 | 1.000         |
| 2   | CFA      | 0.200           | 2.400 | 0.00086  | 6.858           | 2.310 | 0.00089  | 1.035 | 2.679         |
| 3   | POSFA    | 0.200           | 1.590 | 0.00230  | 0.333           | 1.860 | 0.00270  | 1.174 | 16.468        |
| 4   | PFA      | 0.200           | 2.500 | 0.00170  | 0.329           | 2.517 | 0.00670  | 3.941 | 290.972       |

Structural ductility of high-strength reinforced concrete beams for all specimens is given in Table 1. According to Table 1, it could be clearly seen that the use of geopolymer flyash and industrial waste material used in this research, both as cement replacement and aggregates substitution could enhance significantly the ductility of beams. The highest increase was achieved on PFA beam.

4. Conclusions

The use of environmentally friendly and sustainable geopolymer flyash as well as industrial waste material, i.e., coal flyash, palm oil blast furnace slag and pozzolanic flyash both for cement replacement and aggregates substitution which added iron ores as filler could increase the torsion capacity, torsional resistance and ductility of HSRC beams, better than plain HSRC beam. The highest increase in torsion capacity was given by the beam added with pozzolanic flyash followed then with coal flyash.

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