Shear Capacity Analysis of High-Strength Reinforced Concrete Beams using Geopolymer Flyash and Palm Oil Blast Furnace Slag as Additives and Aggregate Substitution

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Abstract. High-strength concrete made with a lot of cement, aggregates and super plasticizer leading to expensive cost. On the contrary, manufacturing of cement is un-environmental friendly because it needs high fuel consumption and releases the CO2 emission to the atmosphere. Moreover, the availability of aggregates coming from river and natural rock decreases over time. This research aims to analyze shear capacity of high-strength reinforced concrete (HSRC) beams added with geopolymer flyash i.e., 15% coal flyash (CFA), 10% pozzolanic flyash (PFA) and 15% palm oil blast furnace slag ash (POSFA) from cement weight as additives; 10% palm oil blast furnace slag (POSS) and 20% pozzolanic sand (PSS) as fine aggregate substitution; and 40% palm oil blast furnace slag as coarse aggregate substitution (POSCA). One plain beam without flyash and aggregate substitution (PBHSC) was tested as comparison. Shear capacity of beams was tested by giving a concentrated load which divided then into two point load (third point loading). Result of shear test showed that all beams experienced shear failure as planned, obtained by applying the actual capacity ratio of flexure to shear 2.29. Aggregate substitution from palm oil blast furnace slag both as fine and coarse aggregates could enhance shear capacity of HSRC beam compared with plain beam. The hardness of palm oil blast furnace slag contributed to this increase, which has wearing value not much different than split, i.e., 4.7% compared with 6.7%. Utilization of flyash did not contribute to the increase of shear capacity as well, although its compressive strength enhanced when compared to PBHSC.

1. Introduction

High-strength concretes made by using a lot of cement, aggregates with highest quality and require additives and super plasticizer leading to expensive cost. They offer many advantages such as high load bearing capacity, good durability and serviceability which make them well-matched to be used for advanced infrastructures. Furthermore, due to increased strength, saving of structural dimension and reinforcement make them more efficient to be used than normal-strength concretes [1].

However, cement production at the plant is not environmental friendly. It needs high fuel consumption to refine the clinkers with a temperature more than 1500^{o}C and releases the CO_2 emission to the atmosphere. Manufacturing of 1 ton Portland cement delivers 1 ton CO_2 to the atmosphere which results in greenhouse effect as the cause of global warming and leads eventually to the climate change [1, 2]. Besides, the availability of aggregates coming from river and natural rock decreases over time.

Based on these, efforts in reducing the cement content to produce high-strength concretes with other cementitious materials are much-needed, beside to reduce the dependence on natural aggregates. Through the use of these substitution materials it is expected that they can still generate the same mechanical properties and durability as the cement based high-strength concretes. This could be achieved by utilizing materials which are available abundant in nature to produce the cost-effective and environment-friendly high-strength concretes. Alternative that can be done is the use of geopolymer flyash as additives for cement replacement and environmentally friendly palm oil blast furnace slag as fine and coarse aggregates substitution [1]. Coal flyash is the waste material from electricity steam power plant having higher fineness than cement grains, and palm oil blast furnace slag is palm oil processing residue that when used for concrete it just needs to be refined and sieved. So it can be concluded that processing of such materials is environmental friendlier than cement production.

The flexural capacity of high-strength reinforced concrete beams using flyash geopolymer as cement replacement, i.e., coal flyash and pozzolanic flyash as well as palm oil blast furnace slag and pozzolanic sand as fine aggregate substitution has been investigated in [1]. The results showed that replacing 15% cement with coal flyash and 10% cement with pozzolanic flyash as well as 10% palm oil blast furnace slag and 10% pozzolanic sand as fine aggregate substitution could enhance bending behavior of the beams significantly, especially in flexural capacity, deflection and ductility.

Geopolymer is inorganic polymer having high content of alkaline, alumina and silica which possesses cementitious characteristics so that it can be used as additive in concrete. Coal flyash is the coal burning waste possessing hydraulic characteristics. Another geopolymer additive is natural pozzolan. It is a sedimentation material from volcanic ash which contains silica alumina compound in an amorphous form. When mixed into concrete it will react with $Ca(OH)_2$ to form Calcium Silicate Hydrate (CSH) and Calcium Alluminate Hydrate (CAH) compound, which could increase the concrete strength.

Palm oil blast furnace slag is a solid waste from the burning of bunches, fibers and shells of crude palm, which has pozzolanic properties because it contains silica component in a big amount. The availability of crude palm is quite abundant in Indonesia. In 2014 there were 10.9 million hectares of crude palm plantation with a crude palm oil production of 29.3 million tons, generating 60% palm waste [1]. The waste of crude palm burning at high temperature produces hard slag which is known as palm oil blast furnace slag. The ash of such slag is a biomass containing high SiO_2 content that is potential to be used as additive and fine aggregates [1].

Beams loaded with bending withstand at the same time shear force. Shear force and bending will occur along the structure holding shear force and bending moment, by establishing the equilibrium of shear force and maximum normal stress in a field that forms a slope to the beam axis.

Cracking due to diagonal tensile stress either occuring only as a result of shear or combined with bending is one of characteristics of the shear damage occurrence. At shorter shear span, the damage occurs as a combination of shear, spalling and splitting, while for beam with longer shear span, cracks due to flexural tensile stress will occur first before cracking due to diagonal tensile stress.

It is well known that failure of reinforced concrete beam due to shear is critical and brittle. The beam will collapse suddenly without any prior notice. On these bases, researches on the shear capacity of reinforced concrete beam are absolutely necessary.

T. B. Aulia et al [1] stated that shear failure of the beam would occur when the actual capacity ratio of flexure to shear was more than 2. Further, B. Bae et al [3] in their experiment concluded that the beam without stirrups having a shear span to depth ratio 3,5 and 2 induced the shear failure. According to [4] testing of shear failure could be carried out by putting the stirrups in a large distance each other in the shear region at a distance of 1/3 beam span from the beam support.

Calculation of flexural and shear capacity of reinforced concrete beam referring to ACI-318 provisions [5], whose calculation analysis has been applied in [1, 6].

M. Coo and T. Pheeraphan [7] revealed that shear capacity of reinforced preplaced aggregate concrete beam decreased as more cement replaced with flyash and limestone powder. The flyash used was Type F conforming to ASTM C618 [8].

Nevertheless, shear capacity analysis of high-strength reinforced concrete beam added with geopolymer flyash, which is available abundant in the nature, and by utilizing waste material as additives and natural aggregate substitution, which has a beneficial effect to environmental preservation, is still scrimpy studied.

Therefore, this work attemps to obtain shear capacity of high-strength concrete beam using geopolymer flyash i.e., coal flyash, pozzolanic flyash as well as palm oil blast furnace slag ash and application of palm oil blast furnace slag and pozzolanic sand as fine and coarse aggregate substitution. The main purpose is to get an effective and efficient high-strength concrete possessing a high serviceability, durability, sustainability and environmentally friendly.

2. Experimental program

2.1. Materials

The coal flyash used came from the coal powered electricity power plant in Nagan Raya Regency, Aceh, having the chemical content composition according to [1] as follows: SiO_2 = 26.65%, Al_2O_3 = 9.6%, Fe_2O_3 = 17.56%, and SO_3 = 2.51%. The content of SiO_2, Al_2O_3, and Fe_2O_3 of coal flyash is 53.81% which is classified into Class C flyash according to ASTM C.618, with a minimum SiO_2, Al_2O_3, and Fe_2O_3 content about 50% [8].

The pozzolanic flyash which originated from Beurandeh Village, Krueng Raya Subdistrict, Regency of Aceh Besar was used in this research whose chemical composition referring to [1], i.e., SiO_2 = 42.96%, Fe_2O_3 = 1.92%, CaO = 0.42%, MgO = 0.28%, Na_2O = 0.13%, K_2O = 0.36%, and TiO_2 = 0.12%. Their physical characteristics were 1.21 kg/l for the bulk density and 2.375 for fineness modulus. For the need as fine aggregate substitution, pozzolanic sand was used in the form of coarser grains. Further, palm oil blast furnace slag used has chemical composition as follows: SiO_2 = 34.11%, Al_2O_3 = 3.57%, Fe_2O_3 = 2.06%, and SO_2 = 0.2% in accordance with the characteristics used in [1].

As additives, coal flyash was used in amount of 15%, which is abbreviated as CFA; pozzolanic flyash with a dosage of 10%, abbreviated as PFA; and palm oil blast furnace slag ash as much of 15%, abbreviated as POSFA; each from cement weight respectively. Furthermore, 10% palm oil blast furnace slag (POSS) and 20% pozzolanic sand (PSS) were applied as fine aggregate substitution. Hereinafter, 40% palm oil blast furnace slag was used as coarse aggregate substitution (POSCA). Finally, one plain beam without flyash and aggregate substitution either as fine and coarse aggregates (PBHSC) was cast and tested as comparison.

Mix design with a w/c-ratio 0.30 comprising of 600 kg/m^3 Portland cement type I content and 1.5% polycarboxylate ether based super plasticizer Viscocrete-10 from the cement weight was used in the concrete mixtures. Split with a maximum diameter of 4.76 mm (2-5 mm) was used as fine aggregate and split with a maximum diameter of 12 mm (5-8 and 8-12mm) was used as coarse aggregate.

To obtain compressive strength, cylinders with a diameter 150 mm and height 300 mm were cast and tested, and plain concrete beams with a dimension of 150 x 150 x 600 mm were tested to get the flexural tensile strength. Testing of flexural tensile strength was executed by loading the beam with concentrated load at two points each at 1/3 span of the beam. The compressive strength and flexural tensile strength were tested at 28 days.

The beam specimens had a dimension of 150 x 300 x 2200 mm and were designed to experience shear failure. To guarantee such failure mechanism to occur, all beams were reinforced with 4 D 18.9 mm for flexural tensile reinforcement, 2 D 15.8 mm for compressive reinforcement and Ø5.68 mm – 300 mm for stirrups. The flexural reinforcement had a yield point of steel (f_y) 462.24 MPa and the shear reinforcement owned a yield point 423.46 MPa. The 28 days compressive strength of PBHSC was 60.65 MPa resulting in the actual capacity ratio of flexure to shear 2.29. Shear behavior of the high-strength reinforced concrete beams containing flyash and aggregate substitution was then compared with the plain beam PBHSC.

Specimens were tested at the age of 28 days after casting with the observed parameter comprising the crack propagation including the load at first crack, crack pattern, maximum shear load, beam deflection, deformation and strain of stirrups and concrete, as well as failure pattern of the beams.

2.2. Instrumentation and testing

To measure deflection, seven LVDTs (Linear Variable Displacement Transducer) were put along the beam, and to record the strain of reinforcements, three strain gauges were installed on the stirrups. Furthermore, two strain gauges were placed at the shear region and maximum bending region in the middle of the beam to measure the concrete deformation.

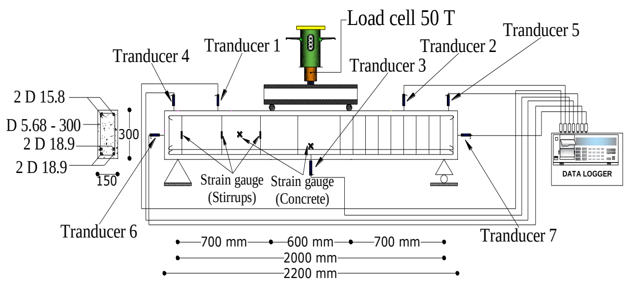

Figure 1. Testing and specimen setup.

Testing of the shear capacity of beams was performed by giving a concentrated load through a hydraulic jack connected to the load cell. The load was then divided into two point load (third point loading) and was increased incrementally for every 100 kg until the specimens collapsed. Deflection and deformation of the beams were recorded using the portable data logger TDS-032. The occurring crack pattern was observed visually and sketched then on the beam surface together with the imposed load. The testing setup of specimens was exhibited in Figure 1.

3. Experimental results and discussion

3.1. Compressive and flexural tensile strength of concrete

According to the compressive testing results of cylinder control specimens it is shown that almost all specimens produce higher compressive strength in comparison with the plain concrete without flyash and aggregate substitution (PBHSC) except for high-strength concrete containing palm oil blast furnace slag as additive (POSFA).

High-strength concrete added with 40% palm oil blast furnace slag as coarse aggregate substitution (POSCA) reached the highest compressive strength 67.50 MPa, followed with 20% pozzolanic sand as fine aggregate substitution (PSS) 66.68 MPa, with 10% pozzolanic flyash (PFA) 66.42 MPa, with 15% coal flyash (CFA) 64.56 MPa, as well as with 10% palm oil blast furnace slag as fine aggregate substitution (POSS) 63.89 MPa respectively, while plain high-strength concrete without flyash and aggregate substitution (PBHSC) generated 60.65 MPa. The lowest compressive strength which was lower than plain concrete (PBHSC) was obtained in concrete containing 15% palm oil blast furnace slag as additive (POSFA) i.e., 58.77 MPa.

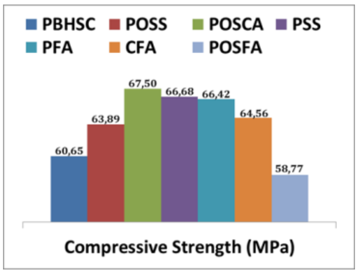

Figure 2. Compressive strength of concrete.

Enhancement of compressive strength on the high-strength concretes containing flyash and aggregate substitution was generated by pozzolanic effect of those geopolymer flyash, which comprises high cementitious materials in form of SiO_2, Al_2O_3 and Fe_2O_3, as well as the hardness of palm oil blast furnace slag which has a quite high wearing value in comparison with split, i.e., 4.7% to 6.7%. Almost similar, pozzolanic sand and slag utilized as fine aggregate substitution have a significant portion of pozzolanic and cementitious materials, where a part of such materials could be eroded during casting and binding then the $Ca(OH)_2$ generated by primary hydration process to form extra Calcium Silicate Hydrate (C-S-H) which played an important role in improving the compressive strength of concrete. Results of concrete compressive strength for each concrete mixtures used in this study were given in Figure 2.

Results of the concrete flexural tensile strength can be seen in Figure 3. Related to the flexural tensile strength, high-strength concretes added with pozzolanic sand (PSS) resulted in the highest tensile strength, i.e., 6.62 MPa, followed by 6.39 MPa for POSCA and 6.09 MPa for PFA, which were higher than the plain high-strength concrete without flyash and aggregate substitution (PBHSC), that was 5.35 MPa. Furthermore, concretes with POSFA and CFA produced a slightly smaller flexural tensile strength, i.e., 5.01 MPa and 4.80 MPa respectively, when compared with PBHSC, while high-strength concrete containing palm oil blast furnace slag as fine aggregate substitution (POSS) earned the lowest, that was 3.67 MPa. Higher cementitious content in flyash and slag yielded good bond strength at interface causing better interlocking between aggregates and cement pastes.

On the contrary, porous palm oil blast furnace slag could generate easier cracks formation at the fine aggregates contributing to a lower tensile strength and elasticity modulus of concrete, as shown by concrete with POSS. Flexural tensile strength of concrete is an indicator for the formation of initial cracks in concrete. The first crack will appear when the flexural tensile strength of concrete is exceeded.

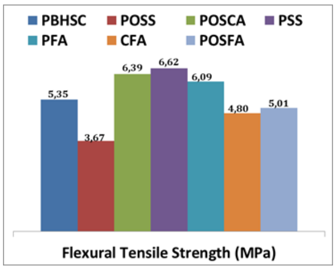

Figure 3. Flexural tensile strength of concrete.

3.2. Shear testing of high-strength reinforced concrete beams

3.2.1. Load and deflection. The relationship between load and deflection in the middle of beam span for all tested high-strength reinforced beams is shown in Figure 4. It could be seen that three main regions were formed during loading, i.e., initial crack area, yield strength area and maximum load area.

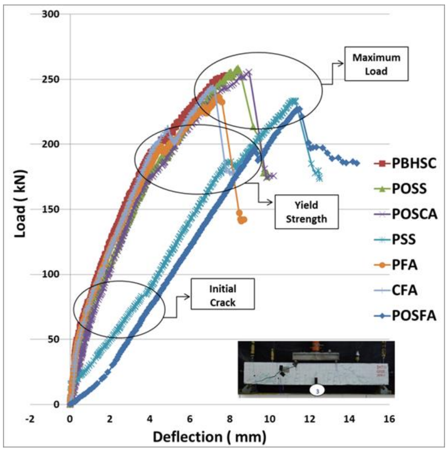

Figure 4. Load and deflection at beam mid-span.

According to the graphs, palm oil blast furnace slag used as aggregate substitution both for fine and coarse aggregate produced the highest shear capacity, that was 258.393 kN for POSS and 255.352 kN for POSCA. The resulting deflection was 8.420 mm for POSS and 8.970 mm for POSCA. These arising loads and deflections were better than plain high-strength reinforced concrete beam (PBHSC) i.e., 252.997 kN and 7.860 mm. Shear capacity and deflection of other high-strength reinforced concrete beams tested in this research program were lower than those of PBHSC, i.e., 243.579 kN maximum load which corresponding to a deflection of 7.190 mm for CFA, 236.810 kN and 7.440 mm for PFA, 233.378 kN and 11.280 mm for PSS, as well as 227.001 kN and 11.500 mm for POSFA.

At initial crack region within elastic phase, POSS beam experienced the first crack at a load of 52.385 kN corresponding to the deflection of 0.590 mm, which occurred above the average of concrete flexural tensile strength of 35.953 kN. The POSCA beam underwent the first crack at a load of 84.561 kN with a deflection of 1.540 mm, which also occurred above the average of concrete flexural tensile strength of 62.666 kN. Further, the first crack at PBHSC beam occurred at 51.109 kN having a deflection of 0.400 mm, which was very close to the average of concrete flexural tensile strength of 52.492 kN. The CFA beam underwent the first crack at a load of 54.445 kN resulting in a deflection of 0.530 mm, which was adjacent to the average of concrete flexural tensile strength of 47.068 kN. The PFA beam cracked firstly at a load of 46.989 kN generating a deflection of 0.360 mm, which occurred below the average of concrete flexural tensile strength of 59.732 kN. The PSS beam met the first crack at 57.486 kN resulting in a deflection of 2.320 mm, which occurred adjacent to the average of concrete flexural tensile strength of 64.892 kN. Finally, the initial crack at the beam added with palm oil blast furnace slag ash (POSFA) occurred at a load of 58.859 kN with a deflection of 3.350 mm, which was above the average of concrete flexural tensile strength of 49.157 kN. It could be clearly seen that the use of such geopolymer flyash and slag as additives and aggregate substitution could increase the first crack load of high-strength reinforced concrete beams except for PFA beam.

According to Figure 4 it could be observed that the beams containing POSS, POSCA, PFA and CFA developed the load – deflection behaviour in a close manner with PBHSC signifying that such durable, environmentally friendly and sustainable materials could be utilized in producing the high-strength concrete having good shear capacity. On the other hand, the beams added with POSFA and PSS generated a sloping and flatter load – displacement curves compared with other beams indicating a lower stiffness but better in ductility.

3.2.2. Load and strain of shear reinforcement (Stirrups). The graphs of all load and strain relationships of shear reinforcement (stirrups) were given in Figure 5. Based on the relationships between load and strain of stirrups it could be noticed that POSFA beam owned the highest shear reinforcement strain in amount of 388.367 με at the load 227.001 kN, followed by CFA beam which had 371.508 με at the load

243.579 kN, POSS beam possessed 85.476 με at the load 258.393 kN, and POSCA beam resulting in 80.130 με at the load 255.352 kN. It could be observed that all mentioned beams demonstrated a better post - yield deformation compared with PBHSC beam which generated the shear reinforcement strain amounting to 57.455 με at the load 252.997 kN. This was indicating a more ductile behavior of the beam.

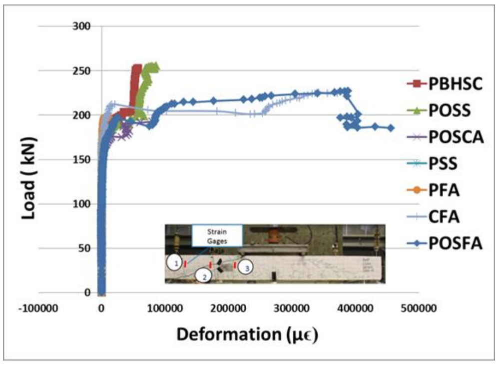

Figure 5. Load and strain of shear reinforcement (Stirrups).

Ductility improvement of stirrups at palm oil blast furnace slag beam either used as fine aggregate substitution (POSS) and as coarse aggregate substitution (POSCA) occurred simultaneously with the shear capacity increase. Furthermore, PSS beam developed 17.914 με at the load 233.378 kN, and PFA beam yielded the lowest shear reinforcement strain, i.e., 10.445 με at the load 236.810 kN.

3.2.3. Load and strain of concrete. Comparison of the relationships between load and concrete strain for all beams analyzed in this research program was given in Figure 6. The maximum concrete strain was generated by the plain high-strength concrete beam without flyash and aggregate substitution (PBHSC) having concrete strain in amount of 131.464 με at a load of 252.997 kN.

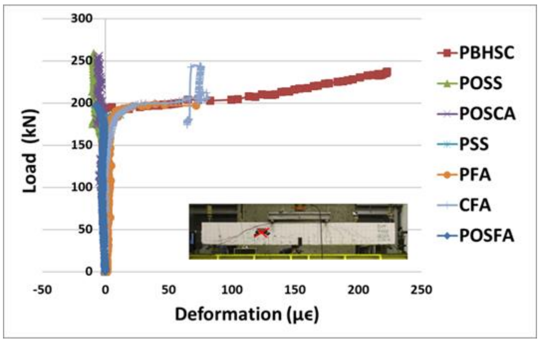

Figure 6. Load and strain of concrete at shear span.

Based on Figure 6, it could be concluded that high-strength reinforced concrete beams having large shear capacity resulted in small concrete strains at the shear zone of beam, as shown by POSS and POSCA beams. POSS beam produced -9.350 με concrete strain at the load 258.393 kN and POSCA beam resulted in 6.223 με concrete strain at the load 255.352 kN. This explained the brittle behavior of shear failure of the beam.

On the contrary, the use of flyash as cement replacement generated relatively larger strains of concrete as shown by CFA, PFA and POSFA beams. CFA beam yielded 74.869 με concrete strain at the load 243.579 kN, PFA beam produced 71.823 με concrete strain at the load 236.810 kN, as well as POSFA beam resulted in 70.099 με concrete strain at the load 227.001 kN. The relatively smaller shear capacity and higher ductility of stirrups allowed for a gradual formation of concrete strain until it reached their ultimate strains which were supported by the development of relatively high compressive strength and flexural tensile strength of concrete.

3.2.4. Failure pattern. Failure pattern of each beams containing various geopolymer flyash as cement replacement and slag as fine and coarse aggregate substitution testing with third point bending load, as well as the plain high-strength reinforced beam, compared sequentially with each other in the same scale, was given in Figure 7. Crack propagation in accordance with the applied incremental load was also drawn in detail at the pictures. According to the pictures, most of arising cracks were shear cracks occurred at shear span directing diagonal to the two loading point (diagonal tension cracks), combined with a few flexural cracks at the pure bending zone. Firstly, the flexural cracks occurred vertically at the pure bending zone of beam, but not continuing upwards to the compressive zone, while due to incrementing load generated simultaneously many shear cracks in the shear span area. The beams failure began with the spreading and propagating of shear cracks becoming the main shear macrocracks at the supporting region. Such damage mechanisms showed the shear failures as planned. From Figure 7 it could be clearly observed that high-strength concrete beams containing palm oil blast furnace slag as fine aggregate substitution (POSS) and coarse aggregate substitution (POSCA) had more shear cracks and crack branches than others showing a better shear resistance. Furthermore, the beam substituted with other fine aggregate (PSS) did not show this tendency because of the low strength of pozzolanic sand it self.

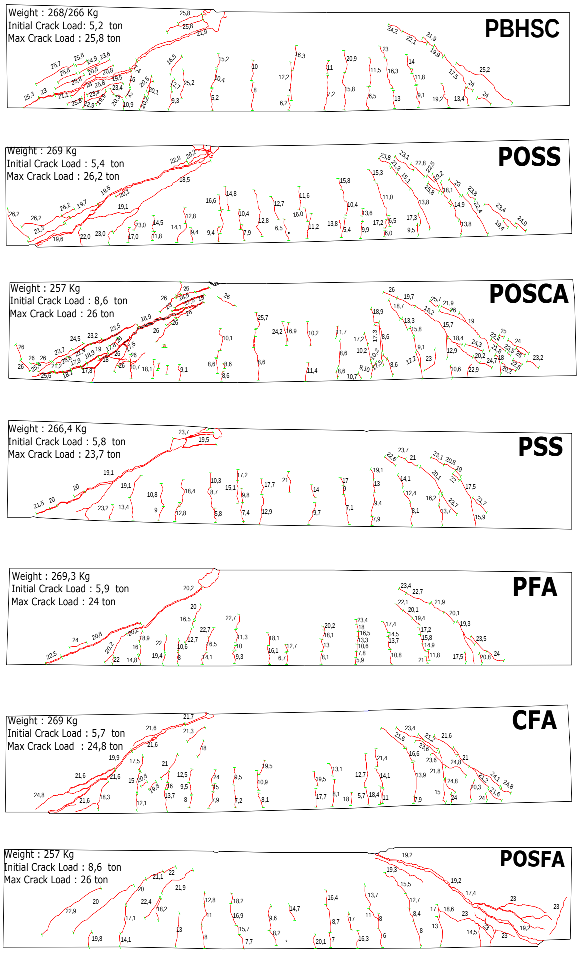

Figure 7. Failure pattern of high-strength reinforced concrete beams.

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4. Conclusions

The environmentally friendly palm oil blast furnace slag used as aggregate substitution both for fine and coarse aggregate could increase the shear capacity and shear resistance of high-strength concrete beam, better than plain high-strength concrete beam. However, the beam added with pozzolanic sand as fine aggregate substitution did not show this tendency due to its low strength.

The sustainable geopolymer flyash used as cement replacement in this research program did not contribute to improve the shear capacity of high-strength reinforced concrete beam, although having better compressive strength in comparison with plain high-strength reinforced concrete beam. This was caused by brittle behaviour of the beam, shown by a small beam deflection.

Acknowledgments

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References

[1] Aulia T B, Afifuddin M and Opirina L 2016 "Bending Capacity Analysis of High-strength Reinforced Concrete Beams Using Geopolymer Fly Ash and Environmentally Friendly Slag as Fine Aggregate Substitution," *Proceedings of The 7th Civil Engineering Conference in the Asian Region (CECAR7), Waikiki, Hawaii, USA, August 30 – September 2*.

[2] Malhotra V M 1987 *Supplementary Cementing Materials for Concrete* (CANMET Canada).

[3] Bae B-I, Choi H-K and Choi C-S "Flexural and Shear Capacity Evaluation of Reinforced Ultra-high Strength Concrete Members with Steel Rebars," *Key Engineering Materials* **577 – 578** pp 17 – 20 (Trans Tech Publications, Switzerland).

[4] Cheng B and Ran Q 2011 "Experimental Study on New Methods for Strengthening Shear Capacity on Concrete Beam," *Applied Mechanics and Materials* **94 – 96** pp 252 – 257.

[5] ACI Committee 318 2005 *Building Code Requirements for Structural Concrete* (ACI 318-05, Farmington Hills, Michigan).

[6] Aulia T B and Rinaldi 2015 "Bending capacity analysis of high-strength reinforced concrete beams using environmentally friendly synthetic fiber composites," *Procedia Engineering* **125** pp 1121-1128.

[7] Coo M and Pheeraphan T 2016 "Effect of sand, fly ash and limestone powder on preplaced aggregate concrete mechanical properties and reinforced beam shear capacity," *Construction and Building Materials* **120** pp 581 – 592.

[8] ASTM C618 2003 *Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete* (American society for testing and materials. West Conshohocken, PA, USA. ASTM International).