Reventing brittle hybrid high-strength reinforced concrete slab collapse due to punching shear using coal flyash substitution, tie wire fiber and polypropylene fiber

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Abstract. Heavy vehicles crossing a bridge could lead in punching shear failure at reinforced concrete deck slab due to highly concentrated axial compressive load from their wheels. This may occur in a very brittle manner and difficult to fix. Effort in improving punching shear capacity of deck slab is with using high-strength concrete and adding fibers into concrete. However, high-strength concretes are not environmentally friendly because using a lot of cement contributing to large CO2 emissions to the atmosphere during its production, therefore coal flyash is used as a part of cement substitution. Based on these facts, this research aims to analyze punching shear capacity of hybrid high-strength reinforced concrete slabs using coal flyash as cement substitution which added with tie wire fiber and polypropylene fiber. The amount of coal flyash was taken 15% from cement weight as cement substitution, tie wire fiber 2% from concrete volume having aspect ratio l/d of 40 and straight shaped fiber geometry, as well as polypropylene fiber 0.2% from concrete volume. Three hybrid high-strength reinforced concrete slabs of 60 x 60 cm2 (two-way-slab) with a thickness 12 cm, w/c-ratio of 0.30 and concrete cylinder compressive strength of $f'_c = 60$ MPa were made with 15% coal flyash and 2% tie wire fiber (CFA-TWF), 15% coal flyash and 0.2% polypropylene fiber (CFA-PPF), as well as 15% coal flyash and combination of 2% tie wire fiber and 0.2% polypropylene fiber (CFA-TWF-PPF). One plain slab without flyash and fibers (PSHSC) was tested as a comparison. To guarantee the punching shear failure mechanism, the slabs were reinforced with tensile reinforcement of 10 Ø 10.5 mm which was distributed to each direction and tested then by giving a concentrated punching load. The results showed that using of coal flyash substitution and addition of fibers could significantly increase the punching shear capacity and structural ductility of hybrid high-strength concrete slabs with the highest enhance both achieved in CFA-TWF-PPF, i.e., 67.91% for punching shear capacity and 92.82% for structural ductility compared with plain slab PSHSC.

1. Introduction

Punching shear is a failure mechanism occurring in slab structures that are subjected to high concentration of axial load. Such failure generally causes dangerous brittle damage and difficult to repair. However, the rules of reinforced concrete slab design in many countries are more focused on bending capacity neglecting safety due to punching shear failure in the structure. One of the structures to be prone to punching shear failure is the bridge deck slab resulting from heavy vehicles traffic,
which transfers a large concentrated wheel load to the deck slab. Other than that, the floor flat slabs riveting on the columns in the building construction are also at risk for punching shear failure.

Due to difficulties in installation, reinforced concrete slab is often designed without using stirrups as shear reinforcement. As the result, punching shear capacity is fully determined by slab thickness and concrete shear strength without contribution of shear reinforcement.

Investigation of punching shear capacity of reinforced concrete slabs without shear reinforcement had been carried out by [1] with variations in concrete strength of 30 MPa and 60 MPa, slab thickness of 10 cm and 12 cm, using tie wire fiber with fraction volume ($V_f$) of 2.0% from the concrete volume. The findings showed that punching shear capacity was predominantly determined by concrete strength and slab thickness, while tie wire fibers enhanced the punching shear capacity and structural ductility of reinforced concrete slab significantly through its contribution as micro-shear reinforcement. Without using synthetic fibers, in case of the concrete compressive strength was increased from about 36 MPa to 130 MPa, the punching capacity of reinforced concrete slabs rose 42% with longitudinal reinforcement ratios of 1.25%, but when reinforcement ratio increased from 0.94% to 1.48%, the punching capacity increased of about 13%, as reported by [2].

Research on the use of synthetic fibers that are added individually to the concrete mixtures on the punching capacity of reinforced concrete slabs has been widely carried out. Study by [3] using steel fibers with fiber volume ratio 0.5%, 1%, 1.5% in the area d, 2d, 3d from the edge of the column and reinforcement ratio 1.2% reported that slabs having 1.5% steel fiber ratio resulted in highest punching shear capacity. The results showed that the use of steel fibers only in a part of slab which was equal to slab thickness $d$ from column face was adequate to provide optimum increase in both punching strength and ductility behavior. In [4], it was mentioned that variations in concrete strength of 56 MPa and 123 MPa, fiber content of 0, 1, 2, 3%, and types of fibers, i.e., steel fiber, polypropylene fiber and Aramid fiber glass could increase the punching shear strength of 22-66% depending on fiber content, in comparison with similar slabs without fibers. It was concluded that the fibers used had a significant effect on the punching shear capacity and ductility behavior of reinforced concrete slabs. Moreover, with using hooked ended steel fibers of 1.2% and 1.4% on high-strength reinforced concrete slabs of 64.5 MPa, it was reported that steel fibers contributed to the enhance in punching shear capacity of 34% and ductility improvement in cracking behavior [5]. Further, by varying slab thicknesses of 12 mm, 22 mm, 32 mm and 42 mm using 3% steel fibers, it was reported that punching shear capacity of high-strength reinforced concrete slabs was significantly increased with the slab thickness [6].

In addition to steel fibers, polypropylene fibers are widely used to study the punching shear capacity of reinforced concrete slabs. Punching shear capacity of reinforced concrete slabs made with different concrete compressive strength of 20, 30, 40 MPa and different ratios of micro-polypropylene fibers (i.e., 6, 7.5 and 9% from cement weight) was investigated by [7]. It was concluded that micro-polypropylene fibers enhanced punching shear capacity with concrete strength of 20 MPa and 30 MPa by 15% and reinforced concrete slab with concrete strength of 40 MPa by 12% with using 9% micro-polypropylene fibers and showed a significant effect on deformability. Then, an increase in punching shear capacity of reinforced concrete slabs incorporated with 0.5% polypropylene fibers amounting to 15.28% and displacement of 20.14% compared with normal plain slab was reported by [8]. Besides being able to enhance the punching shear capacity, the use of tie wire fibers and polypropylene fibers can significantly increase the bending capacity of high-strength reinforced concrete beams, mainly in terms of flexural strength, ductility and bending behavior as reported by [9].

High-strength concrete made with a lot of cement having a low water to binder ratio, which is added with additives and admixtures. On the contrary, production of cement at factory is not environmentally friendly because it needs a lot of calcium based raw material and releases CO$_2$ emission to the atmosphere during the combustion of clinker at temperatures up to 1500°C. Production of 1 ton cement requires 1.7 tons of natural raw material and on the other, releases 1 ton CO$_2$ into the atmosphere [10]. To reduce the usage of cement, additives containing some chemical compositions those found in cement can be used. One of such additives is coal flyash.
The research using partial substitution of cement with coal flyash, i.e., 15% from cement weight on the mechanical capacity of high-strength reinforced concrete beams had been carried out by [11] on bending capacity, by [10] on shear capacity, as well as by [12] on torsion capacity. The results showed that substitution of cement with 15% coal flyash could generate mechanical properties and mechanical behavior of high-strength reinforced concrete beams that were closer to or even better than entirely cement-based high-strength reinforced concrete beams.

Based on these facts, punching shear performance of high-strength reinforced concrete slab without shear reinforcement by combining geopolymer flyash and hybrid synthetic fibers has not been sufficiently investigated. Therefore, the aim of this study is to find potential solution in preventing sudden failure in structures due to punching shear phenomenon. The use of tie wire fiber and polypropylene fiber as well as coal flyash are on the basis of efficiency, environmental conservation and availability of materials which are relatively inexpensive, in which case tie wire fiber is construction project waste and coal flyash is electric steam power plant waste.

2. Experimental program
2.1 Research method

This research was carried out to determine punching shear resistance of hybrid high-strength reinforced concrete slabs using 15% geopolymer coal flyash as cement substitution which added with 2% tie wire fiber and 0.2% polypropylene fiber both individually and jointly. The resulting punching shear behavior was then compared with plain high-strength reinforced concrete slab without flyash substitution and fibers.

Critical punching shear failure occurs at the perimeter plane of concentrated axial compressive load which is described by the rupture of slab along the surface of axial load to the lowest side of slab surface. The stresses formed by punching shear in a flat slab can be analogous as a two-dimensional shear stress occurring in a beam causing more critical stresses compared with the shear stress of beam. Perimeter of critical area is considered to be at a half distance from column face to the failure tangent with the lower slab surface as shown in Figure 1(a) [13]. Several rules that govern the critical punching shear limits are described in Figure 1(b) [13].

![Figure 1](image)

**Figure 1** (a). Perimeter area of punching shear failure (left); (b). Critical limits on punching shear by several Codes (right).

The specimens used were high-strength reinforced concrete slabs with a concrete compressive strength of 60 MPa, dimension of 60 x 60 cm² and slab thickness of 12 cm. To gain the main mechanical properties of concrete for controlling the characteristics of slabs, concrete compressive strength test using cylinder specimens with a diameter of 15 cm and height of 30 cm and concrete flexural tensile strength test with beam specimens of 15 x 15 x 60 cm were conducted.

The width of slab was taken to be 60 cm according to [13], which must be greater $4d + c_0 = (4 \times 12) + 10 = 58$ cm, where $d$ is the slab width and $c_0$ is width of the steel plate pressing block surface.
(footing) having dimension of 10 x 10 cm with a thickness of 10 cm. It was taken into account to avoid the initial rupture occurred in supporting area.

To prevent bending failure, the slabs were reinforced with tensile reinforcement of 10 Ø 10.5 mm with the yield strength of 240 MPa, which was distributed to each direction (two-way slab) as shown in Figure 2 (a). Amount of tensile reinforcement was obtained from theoretical calculations taking into account the dimension of slab, concrete compressive strength and yield stress of flexural reinforcement. The results were then controlled to be safe against bending ($P_Y \geq 1.5V_c$) and ensured the occurrence of punching shear in the slab structure ($V_n \geq V_c$), where $P_Y$ is flexural strength of slab, $V_c$ is shear strength of concrete, $V_n$ is nominal shear strength occurring in slab structure.

Strain gauges were used to monitor deformations on tensile reinforcement and concrete, each 4 units for reinforcement and 2 units for concrete. Deformations were recorded and read using Portable Data Logger TDS-302. The placement of strain gauges on tensile reinforcement and concrete is given in Figure 2 (b).

![Figure 2](image-url)

**Figure 2** (a). High-strength reinforced concrete slab specimen (left); (b). Placement of strain gauges on tensile reinforcement and concrete (right).

To determine deformability of the slab, ductility index which describes the ability of structure in carrying inelastic deformation prior to collapse was calculated with the following equation $\mu = \Delta_u/\Delta_y$, where $\Delta_u$ is the ultimate deformation and $\Delta_y$ is deformation at first yield. Ductility constitutes structural property which plays an important role in designing earthquake-resistant structures. It is widely used to control brittle collapse of structure.

### 2.2 Materials

The coal flyash used originated from electric steam power plant in Nagan Raya Regency, Aceh, which possessed chemical composition as follows $\text{SiO}_2 = 26.65\%$, $\text{Al}_2\text{O}_3 = 9.6\%$, $\text{Fe}_2\text{O}_3 = 17.56\%$, and $\text{SO}_3 = 2.51\%$ [10]. Amount of $\text{SiO}_2$, $\text{Al}_2\text{O}_3$, and $\text{Fe}_2\text{O}_3$ content is 53.81% which is categorized into Class C flyash referring to ASTM C.618, that has a minimum $\text{SiO}_2$, $\text{Al}_2\text{O}_3$, and $\text{Fe}_2\text{O}_3$ content about 50% [14]. Dosage of coal flyash used was 15% from cement weight.

The fibers employed were tie wire fiber and polypropylene fiber which were used separately and combined into a hybrid composite. The tie wire fibers were cut from the construction reinforcing binding-wire having a diameter of 0.75 mm and a length of 30 mm with tensile strength of 38.5 N/mm$^2$ and specific gravity of 6.60 gr/cm$^3$. The fiber fraction volume ($V_f$) was 2.0% from the volume of concrete.

Polypropylene fibers are plastic-based fibers from the polyolefin family in the form of bundles that made in small bands (fibrils). The use of polypropylene fibers can increase the ductility of concrete by...
employing the higher tensile strength and elastic modulus of the fiber than concrete, polypropylene fibers can bridge cracks formed in the concrete matrix thus slowing crack propagation. The pullout process of polypropylene fibers from the concrete can provide high fracture energy and fracture toughness preventing the sudden collapse of concrete. Besides, polypropylene fiber can function as micro reinforcement for cracking control which is more cost effective than other synthetic fibers. The polypropylene fibers used in this research owned a diameter of 18 microns and a length of 12 mm, thus having the aspect ratio of 66.7.

High-strength concretes were produced using the weight ratio method by trial and error referring to concrete mixture volume of 1,000 liters. Portland cement type I in amount of 550 kg/m³ with a water cement ratio of 0.3, silica fume 8% from cement weight as additive and superplasticizer Sikament NN with a dosage of 2% by cement weight were used to make plain high-strength concrete without using coal flyash and fibers. Aggregates used consisting of fine aggregates from river sand with a maximum diameter of 4.76 mm and coarse aggregates in form of split with a maximum diameter of 15.9 mm.

2.3 Instrumentation and testing
The slabs were tested at the age 28 days. During testing, data about loading, tensile reinforcement strain and concrete strain, deflection, as well as crack pattern of slabs must be collected in detail. The specimen was first placed on the rigid metal frame support mounted rigidly on a steel plate with dimension of 80 x 80 x 10 cm as strong floor, which was connected with the bottom steel frame beam. The testing instruments were installed in a H-beam steel frame of 200 x 100 x 5 mm which attached as columns and beams. Testing was carried out by giving punching load on the pressing block (footing) of 10 x 10 x 10 cm through a hydraulic jack attached to the load cell. Load was continuously increased until the formation of initial cracks and ended until the collapse of slab.

![Set-up of punching shear testing.](image)

Figure 3. Set-up of punching shear testing.

Three Linear Variable Displacement Transducers (LVDTs) were vertically installed on slab, 2 units on the top side to record rotation at the slab ends and 1 unit at the bottom side to record the deflection at the middle of slab. Deformations on tensile reinforcement and concrete were monitored by strain gauges installed each 4 units for reinforcement and 2 units for concrete. All deformations and deflections occurring during testing were recorded using Portable Data Logger TDS-302 and printed automatically on the print paper P-60 installed on the Portable Data Logger. A space with a width of 15 cm between the rigid metal frame supports was provided for the placement of LVDT under the midspan of slab and to put camera for observing crack propagation on the bottom surface of slab during loading. Set-up of punching shear test for flat slab specimens on the steel frame is presented in Figure
3. After testing, slab specimens were moved to observe crack propagation and developing failure pattern visually from both surfaces, bottom side and top side.

3. Experimental results and discussion

3.1 Compressive and flexural tensile strength of concrete

The compressive test results show that all specimens yield higher compressive strength compared with plain high-strength concrete without using coal flyash and fibers (PSHSC) as demonstrated in Figure 4. Hybrid high-strength concrete made with 15% coal flyash and combination of 2% tie wire fiber and 0.2% polypropylene fiber (CFA-TWF-PPF) resulted in the highest compressive strength of 68.59 MPa followed then by high-strength concrete with 15% coal flyash and 2% tie wire fiber (CFA-TWF) of 67.68 MPa, as well as with 15% coal flyash and 0.2% polypropylene fiber (CFA-PPF) amounting to 61.94 MPa respectively. PSHSC itself had a compressive strength of 55.00 MPa.

The same findings were obtained from flexural tensile strength tests as shown in Figure 4, where CFA-TWF-PPF produced the best result amounting to 8.97 MPa, followed by CFA-TWF of 8.40 MPa and CFA-PPF of 7.36 MPa. High-strength concrete without using coal flyash and fibers (PSHSC) earned the lowest flexural tensile strength, i.e., 5.01 MPa.

Increase in compressive strength and flexural tensile strength on hybrid high-strength concretes with coal flyash and fibers, both tie wire fiber and polypropylene fiber, was generated by pozzolanic and filling effect of coal flyash, which composed of high cementitious minerals in form of SiO$_2$, Al$_2$O$_3$ and Fe$_2$O$_3$, as well as contributed by the higher modulus of elasticity and tensile strength of synthetic fibers in comparison with the cement paste in concrete matrix.

Through the pozzolanic effect, the cementitious material on the coal flyash will bind Ca(OH)$_2$ which is formed from the primary hydration process of cement to form extra Calcium Silicate Hydrate (C-S-H) which plays an important role in increasing the compressive strength of concrete. Due to the more finer particle of coal flyash compared with Portland cement particles size, thus a denser matrix with a lower porosity will be created in concrete.

![Figure 4. Compressive and flexural tensile strength of concrete slabs](image)

3.2 Punching shear testing of high-strength reinforced concrete slabs

3.2.1. Load and deflection. The load and deflection relationships at the midst of slab for all investigated high-strength reinforced concrete slabs are described in Figure 5. From these relationships it could be revealed the loads at initial crack, at yield and at ultimate condition of tested slabs during loading history.

Referring to the graphs, hybrid high-strength concrete slab CFA-TWF-PPF yielded the highest punching shear strength, i.e., 34.08 ton resulting in a deflection of 12.98 mm followed by CFA-TWF which earned punching shear capacity of 31.48 ton with deflection of 7.34 mm and CFA-PPF which resulted in maximum punching shear strength of 28.46 ton with deflection of 6.16 mm respectively. Plain high-strength reinforced concrete slab without flyash and fibers (PSHSC) had a lowest punching shear capacity, that was 20.3 ton corresponding with a deflection of 5.17 mm.
Based on the graphs, it could also be observed that the slabs of CFA-TWF-PPF, CFA-TWF as well as CFA-PPF developed the load-deflection characteristics in a close manner each other indicating a higher stiffness and much better ductility in comparison with PSHSC slab which generated a sloping and flatter load-deflection curve. Thus, it could be obviously observed that the use of coal flyash and such synthetic fibers, i.e. tie wire fiber and polypropylene fibers both added individually and jointly could significantly enhance punching shear capacity of high-strength reinforced concrete slabs.

Figure 5. Load and deflection at the midst of slab

3.2.2. Load and deformation of flexural tensile reinforcement. The load and deformation behavior during testing that developed on the flexural tensile reinforcement for all punching shear tested slabs is given in Figure 6. In accordance with those relationships, it could be analyzed that the flexural tensile reinforcements installed in all high-strength reinforced concrete slabs had not reached its yield strain of 0.002 (2000µε) when the slabs reached its ultimate load. This condition justified the assumption of slab reinforcement design where the slab must be safe against bending but will collapse due to punching shear (P_y ≥ 1.5V_c).

Figure 6. Load and strain of flexural tensile reinforcement of slab

The maximum flexural tensile reinforcement strain at ultimate load recorded was 0.0021 (2100µε) yielded by CFA-PPF slab, followed by CFA-TWF-PPF slab of 0.00202 (2022µε), then CFA-TWF slab of 0.00171 (1710µε) and the lowest was reached by PSHSC slab of 0.00153 (1530µε) respectively. Thus, it could be noticed that the slabs made with coal flyash and both fiber types added individually and in combination altogether demonstrated a better post-yield deformation in comparison with plain slab PSHSC, signifying a better ductile behavior. In other words, it means
that the use of those coal flyash and fibers could delay the attainment of tensile reinforcement yield strain at a higher load.

3.2.3. Load and strain of concrete. The load and concrete strain relationships of all high-strength reinforced concrete slabs investigated in this study were compared each other in Figure 7. Hybrid high-strength reinforced concrete slab CFA-TWF-PPF generated the maximum concrete strain at ultimate load in amount of 0.00265 (2650 µε), followed by CFA-TWF slab of 0.00201 (2010 µε), then CFA-PPF slab of 0.00092 (920 µε), and PSHSC slab resulted in the lowest concrete strain of 0.003 (300 µε) respectively. According to Figure 7, it could be noticed that high-strength reinforced concrete slabs containing coal flyash and fibers that had higher punching shear capacity generated larger concrete strain due to punching load, explaining the concrete rupture at the perimeter plane of the given concentrated axial compressive load, which became critical punching shear failure.

![Figure 7. Load and strain of concrete.](image)

3.3 Ductility and failure pattern of high-strength reinforced concrete slab

Structural ductility of high-strength reinforced concrete slabs is calculated with the formula $\mu = \Delta_u/\Delta_y$, where $\Delta_u$ is the ultimate deflection and $\Delta_y$ is deflection at yield point of structure. Hybrid high-strength reinforced concrete slab CFA-TWF-PPF generated the highest ductility, that was 3.222 followed by CFA-TWF slab of 2.324, after that CFA-PPF slab of 2.038 and PSHSC slab of 1.671 respectively. In comparison to plain slab PSHSC, there was a very significant increase in ductility of hybrid high-strength reinforced concrete slabs containing coal flyash and fibers, i.e., 92.82% for CFA-TWF-PPF, 39.08% for CFA-TWF as well as 21.96% for CFA-PPF.

Failure pattern on the bottom surface of punching shear tested slabs is given altogether in Figure 8. Punching shear failures on the bottom slab surface shown in Figure 8 revealed almost the identical crack pattern for all tested slabs, unless it differed only in the number of cracks developed. Plain high-strength reinforced slab PSHSC showed less number of cracks in comparison with slabs containing coal flyash added with fibers. Crack propagation was firstly initiated by micro cracks occurred due to flexural behavior arising in the midst of slab. These initial cracks developed after the concrete flexural tensile strength was exceeded by load increment. Then the cracks propagated further with a diagonal pattern accompanied by emerging new cracks which formed branches and spread continuously to the entire slab surface until the emergence of spalling on concrete at peak load.

Cracking propagation on the top face of slab was initiated by penetration of steel plate pressing block as load carrier to the concrete in the footing vicinity area of about 2 cm deep. In the high-strength reinforced concrete slabs with coal flyash and fibers, punching shear failure occurring on the top surface emerged after ultimate concrete strain was exceeded. The cracks started from the perimeter of footing face but did not develop to the outside of footing area at all. Conversely, at the plain high-
strength reinforced concrete slab, after occurring in the perimeter of footing, the crack propagated further to the outside of footing area with a diagonal propagation direction as shown in Figure 9.

![Figure 8. Failure pattern on the bottom surface of slab](image1.png)

![Figure 9. Failure pattern on the top face of slab](image2.png)

4. Conclusions
The geopolymer coal flyash used as cement substitution and tie wire fiber as well as polypropylene fiber that could contribute as micro-shear reinforcement added both individually and in combination altogether could increase significantly the punching shear behavior of hybrid high-strength reinforced concrete slabs, better than plain high-strength concrete slab. The highest enhance in punching shear capacity was given by the hybrid high-strength reinforced concrete slab added with coal flyash as cement substitution and both tie wire fiber and polypropylene fiber altogether. Thus, the use of such
materials could provide inexpensive and environmental friendly high-strength reinforced concrete slabs contributing to the environmental preservation, because coal flyash and tie wire fiber are industrial and construction project waste.

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