Punching shear behavior of rubberized concrete slab

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Abstract. Punching shear of flat slabs made from normal concrete is a local, brittle failure that may occur before the ductile flexural failure. Since the concrete technology introduced alternative materials into concrete to promote the sustainability by using recycle material such as agriculture waste and industrial by product, the quality of this concrete need to be investigate further in all aspect. Therefore, this study is initiated to investigate the performance of concrete containing rubber to be used as structural element. This study is investigated the behavior of rubberized concrete flat slab subjected to the punching load. The effect of rubberized concrete and different slab thickness to the punching shear strength is main consideration in this investigation. The study is started by evaluating the mechanical properties of rubberized concrete such as compressive strength, flexural strength and splitting tensile strength. In comparison to normal concrete, the mechanical properties of rubberized concrete shown a reduction in compressive strength and increase in flexural strengths and split tensile strength. The performance of rubberized flat slab is observed in term of punching shear strength, critical perimeter and displacement by using experimental approach. Punching shear strength and development of crack within critical perimeter are observed during experimental test. Punching shear strength produced by experiment test is compared to values obtained by established equations from EC2 and ACI 813. From this comparison, it is indicated that the equations are over predicted the punching shear strength in the range of 12 – 72 %. Rubberized concrete slab exhibited ductile failure and underwent significant displacement before reaching punching fracture. Critical perimeter produced by rubberized concrete slab also extended more than produced in the normal concrete in the range of 34 - 75%. The punching shear strength of rubberized concrete slab also exhibited a significant reduction in punching shear resistance compared to normal concrete for the similar slab thickness. As conclusion, the rubberized concrete produced better critical perimeter at the lower punching shear resistance.

1. Introduction
In today modern industrial era, large and mega construction activities taking place everywhere, hence there will be a shortage of land space, so the construction of tall structures has been triggered up to overcome this problem. There are several elements are modified to make construction work faster and economical like introducing of flat slab, precast element and prestressed element which able to reduce dead weight and makes beams invisible, enhances floor area. New construction element and method need to satisfy all design requirements where the performance of the structure should be tested against all type loadings, all seismic zones factors, and various soil categories then only we can extract the best choice or suitability parameter for the structures.

One of the popular choices to suit the needs of speed construction is flat slab. The flat slab is a reinforced concrete slab supported directly by concrete columns without the use of beams. The flat
slab is defined as a one-sided or two-sided support system with a shear load of the slab being concentrated on the supporting columns. In general, slabs are susceptible to a type of local failure known as the 'punching shear failure' under concentrated loads or over the supporting columns. Punching shear is a type of failure of reinforced concrete slabs subjected to high localized forces. In flat slab structures, this failure likely occurs at column-slab joint. The failure is possible due to high shear concentration at a joint. This type of failure is catastrophic because no visible signs are shown prior to failure. Punching shear failure disasters have occurred several times in this past decade. A typical flat slab punching shear failure is characterized by the slab failing at the intersection point of the column. This results in the column breaking through the portion of the surrounding slab. This type of failure is one of the most critical problems to consider when determining the thickness of flat plates at the column-slab intersection. Accurate prediction of punching shear strength is a major concern and absolutely necessary for engineers so they can design a safe structure.

Conventional principle does not apply when considering the mechanism of a punching shear failure; in a slab system with a concentrated load or at a slab-column connection, the loaded area is not actually pushed through the slab. Punching shear failures arise from the formation of diagonal tension cracks around the loaded area.

Punching shear happens at the column-slab connection, and if the punching shear is high the connection could lose its shear and bending capacity, and consequently leads to a total collapse of the structure. The design against punching failure is, therefore, one of the most important factors in structural design. Nowadays, there are few options to predict the behaviour and strength of punching shear of flat slabs using developed techniques such as finite element analysis and artificial neural network modelling [1, 2].

As for now the available prediction equation for punching shear is reported by the established design codes is only applicable for normal concrete such as in BS8110-97, Euro-code 2, and ACI 318-11. One of the significant parameters used in the calculation of punching shear is critical perimeter which associated with effective depth of the slab. Since the critical perimeter is depending on the formation of the conical shape of the crack and it is expected to be different if different quality of material is used. Nowadays, the rubberized concrete is getting attention among researchers [3-8] which possible to be used commercially. Therefore, it is important to evaluate the behavior and formation of cracks due to punching for the rubberized concrete flat slab to predict the critical perimeter.

Scrap tires continue to be an environmental problem; therefore, research continues on discovering advanced ways of utilizing this waste material in a more environmentally friendly means. Scrap tires in the form of crumb rubber, shredded tyre/rubber can be meaningful to be used as alternative materials. Recently, the substitution method is one of optional that effectively been used to replace the natural aggregates by rubber [9]. From construction material perspective, the properties of material to be acceptable as an engineering material should fulfill and satisfy the requirements set by related standard and guidelines. Reduction in compressive strength and modulus of elasticity of rubberized concrete by 22% and 7% is obtained by Nabilah et al. [8]. It was found that the rubber reduces the workability of the mix, which subsequently decreases the mechanical properties of concrete. [9, 10].

The aim of this study is to investigate the structural punching shear performance of rubberized concrete flat slab. Rubberized concrete is developed using rubber crumb as partial replacement for aggregate and metakaolin is used as partial replacement for cement. The mechanical properties test is conducted to measure compressive strength, splitting tensile strength and flexural strength to ensure the quality of concrete.

The structural performance of punching shear is conducted by evaluating the cracking and the critical perimeters developed in rubberized concrete flat slab of different thickness. The efficiency of the experimental results is evaluated by compared the test results to the establish equation from the design codes.
2. Material and method
Materials used in this study consist of binder which represent by ordinary Portland cement (OPC) and metakolin, sand as fine aggregate which had a maximum size of pass-through 4.75mm sieve, crumb rubber in size range of 1mm to 4mm diameter, and coarse aggregate of 20mm maximum size. Metakaolin is used partially by substitute OPC at 15% replacement level. Crumb rubber is used to replace fine aggregate at 10% replacement level. Crumb rubber is treated using sodium hydroxide (NaOH) solution before mixing.

2.1. Mix of concrete
The of mix design calculation used in this study is according to Department of Environment (DOE) based on target strength of 35MPa. The water to binder ratio used is 0.5 and the water content is fixed at 195kg/m$^3$. Two concrete mixes consist of control mix and rubberized concrete mix are prepared.

2.2. Specimens preparation
Moulds should be made in accordance with BS EN 12390-2, testing of hardened concrete. Three types of strength tests are performed to evaluate the hardened rubberized concrete strength namely as compressive strength, flexural strength and splitting tensile strength. The cubes of 100mm x 100mm x 100mm are used for compressive strength, prisms of size 100mm x100mm x 500mm are used for flexural strength and cylinder of size 100mm (diameter) x 200mm is used for splitting tensile strength. This hardened test of concrete is in accordance of BS EN 12390-2.

2.3. Slab
Investigation on punching shear performance of rubberized flat slab is conducted using square slab specimens. A total of three slab specimens of different thickness of 50mm, 100mm and 150mm are prepared which designated as S1, S2 and S3 respectively. The constant length and width of 1100mm x 1100mm slab is considered for all slab specimens in this study. The slab is designed as flat slab according to design standard of BS8110. The details and reinforcement required for each slab is shown in Table 1. The slabs are casted in timber molds.

Table 1. Reinforcement required for each slab specimens.

| Specimens | Thickness (mm) | Concrete cover (mm) | Top reinforcement | Bottom reinforcement |
|-----------|----------------|---------------------|-------------------|----------------------|
| S1        | 50             | 10mm for top and bottom | 5T @ 100mm for longitudinal and transverse directions | 5T @ 100mm for longitudinal and transverse directions |
| S2        | 100            | 25mm for top and bottom | 6T @ 200mm for longitudinal and transverse directions | 6T @ 200mm for longitudinal and transverse directions |
| S3        | 150            | 25mm for top and bottom | 6T @ 125mm for longitudinal and transverse directions | 6T @ 125mm for longitudinal and transverse directions |

2.4. Punching shear test preparation
The tests are performed in Structure Laboratory, UPM. Tests were designed to simulate the actual conditions of flat slab. A test rig, consisting mainly of steel girder with height of 473mm and 1000 kN capacity hydraulic jack was used for the purpose of loading the slabs of various thickness under loading arrangements until failure. The test setup is as shown in the Figure 1.
Each slab was subjected to concentrated loading at the center of slab where this load is also simulating load of column of flat slab. This idealization perfectly represented by a square steel plate of size 20mm thickness x 200mm x 200mm where it is attached on top of surface of slab. This steel plate is placed at central of slab geometry. This concentrated load is supplied by a load cell which supplied it through steel plate by using jack. Four steel blocks were used at each corner of the slab as support. The slab is equipped with two linear variable differential transformer (LVDT) at the center of slab to measure the central slab deflection. These LVDTs are placed at top and bottom of slab. In addition to this, there are eight strain gauges used to monitor the development of strain of slab during test. Four strain gauges are placed at the top surface and another four are placed at the bottom surface of slab. The selected points of strain gauge placement are based on the estimated zone of critical perimeter to be occurred.

Loading was applied to the specimen at an approximately constant rate up to the peak load; at the same time deflections were measured. The loading is statically continued until the failure is pronounced.

**Figure 1.** Punching shear test set up.

### 3. Results and discussion

#### 3.1. Mechanical properties of rubberized concrete

**3.1.1 Compressive strength.** The purpose of compression test is to determine the compressive strength of concrete. The compression tests of this project conducted at 7days and 28days age of concrete. In general, all the concrete samples with rubber aggregates replacement produced a higher strength than the target strength, 35 MPa. The average of three cubes specimens results for 7 and 28 days are tabulated in Table 2. The compressive strength dropped by 32.5 % compared to control. Some obvious observations from these results are that with replacing fine aggregate with rubber which caused to decrease in the compressive strength and weight due to the lack of cohesion between the rubber particles and cement paste and also due to development of voids which might have produced due to the fine nature of crumb rubber.
Table 2. Compressive strength results.

| Mixes          | 7 days (MPa) | Average (MPa) | 28 days (MPa) | Average (MPa) |
|----------------|--------------|---------------|---------------|---------------|
| Control concrete | 43           | 44.6          | 55            | 55.7          |
|                | 45           |               | 56            |               |
| Rubberized concrete | 25.63      | 25.3          | 37.52         | 37.56         |
|                | 25.16        |               | 38.08         |               |
|                | 25.3         |               | 37.08         |               |

3.1.2 Flexural strength. The purpose of the flexural test is to determine the flexural strength of concrete using prism specimens. The four-point bending flexural tests were performed to prism specimens at the 28 days after curing and the results is shown in Table 3. Rubberized concrete produced higher flexural strength by 52% compared to normal concrete for average strength of 6.16 MPa and 4.06 MPa for rubberized concrete and normal concrete respectively. The specimens were capable of withstanding measurable post failure loads and undergoing significant displacement. This was due to the ability of the rubber aggregate to undergo large elastic deformation before the failure of the specimen took place. The failure was initiated in tension region of the prism specimens in which cracks propagated in the cement matrix until they reached the rubber aggregate. When cracks reached the rubber particles and, because of their elastic properties and low modulus of elasticity, the rubber particles prolonged and sustained a portion of the applied load, which leads to an increase in the area of the failure surface.

Table 3. Flexural strength results.

| Mixes          | 7 days (MPa) | Average (MPa) |
|----------------|--------------|---------------|
| Control concrete | 3.8          | 4.06          |
|                | 4.5          |               |
|                | 3.9          |               |
| Rubberized concrete | 5.7       | 6.16          |
|                | 5.9          |               |
|                | 6.9          |               |

3.1.3 Split tensile strength. Splitting tensile test is used to determine the tensile strength of the concrete by performing the test on cylinder specimens at the age of 28 day after curing. The results are tabulated in Table 4. From the results obtained, the split tensile strength for rubberized concrete is higher compared to control concrete. From the results obtained the control specimen resulted in a strength of 3 MPa as tested at the 28th day of curing than rubberize concrete which resulted in 9.6 MPa. This is due to rubber aggregate content which had a good bond to the cement matrix which delayed the formation of crack.

Table 4. Splitting tensile strength results.

| Mixes          | 7 days (MPa) | Average (MPa) |
|----------------|--------------|---------------|
| Control concrete | 3.1          | 3             |
|                | 2.9          |               |
|                | 3.1          |               |
| Rubberized concrete | 10.48     | 9.6           |
|                | 9.04         |               |
|                | 9.29         |               |
3.2. Slab under punching load

3.2.1 Load vs displacement. Result of punching load vs midspan deflection of rubberized concrete flat slabs is shown in Figure 2. These results obtained after performing punching shear test for slab of three different thickness of 50 mm, 100 mm and 150 mm which designated as S1, S2, S3 respectively. The deflection is taken in the middle of slab.

![Figure 2. Punching load vs displacement.](image)

The punching load vs displacement of slab subjected to punching load is shown in Figure 2. The trend shows that, the punching shear capacity is increasing with the increment of the slab thickness. S1 which having the lowest thickness produced 25 kN of maximum punching load followed by S2 and S3 slab with maximum load of 75 kN and 200 kN respectively. Comparison to slab produced by normal concrete for thickness of 50mm has been added to the current data which assigned as CS1 in Figure 2. The results showed ductile behavior for all rubberized slabs but for the control the punching shear achieved was 56 kN but suffers from sudden failure.

From this experimental observation, with the increase of thickness there is noticeable increase in maximum punching load. This result is strongly agreed and reflect to various design equations that considered the thickness (d) as one of the main factors which affect the punching shear.

In comparison to normal concrete slab, the rubberized concrete slab of the same thickness to the normal concrete slab which represented by S1 and CS1, produced lower punching shear capacity. This is due to lower compression strength of rubberized concrete compared to the normal concrete which have direct relation to the punching shear capacity, so by having lower compressive strength the punching shear will be relatively affected.

The reduction in compressive strength can be explained by the lack of cohesion and bond between the rubber particles and cement paste and also due to development of voids which might have produced due to the fine particle of crumb rubber. But the specimens which contained rubber S2 and S3 exhibited post failure ductile behavior and underwent significant displacement before failure as shown in Figure 2. Although all specimens were highly cracked, the specimen were able to withstand the ultimate load with extended displacement.

This finding is consistent with what was observed by Ismail, Hassan & AbdelAleem [11]. Similar effect observed in all the specimen which is large displacement and deformation which were due to the fact that rubber aggregate has the ability to withstand large deformations. Rubber aggregate particles seem to act as springs and cause a delay in widening the cracks and preventing the catastrophic failure which is usually experienced in plain concrete specimens. The failure started at the tension region of the slab in which according to the observation the cracks started at the bottom of the slab in the tension region and from there they propagated. When the crack
reached the rubber particles in mix the rubber prolonged and sustained a portion of the applied load because of its elastic properties. This also caused an increase the ability to deflect and preventing the sudden failure. The first crack started to occur at load of 90 kN for S3 and the crack is appeared at the tensile bottom region of slab. For slab S2, the cracks started to form earlier than slab S3 which is at load of 42 kN. However, for slab S1 the first crack is happened at much lower load than others slab which is at 25 kN load which also identical to the failure load. The first crack was observed to occurred on top surface which showed increase in punching critical perimeter and wider than the normal concrete for S1.

3.2.2 Critical perimeter. Critical perimeter, R is significant parameter used in the calculation of punching shear. The critical perimeter is associated with effective depth of the slab. Hence the critical perimeter is depending on the formation of the conical shape of the crack, during loading stage on punching shear test, the cracks was observed to propagate from face of the column to the vicinity around the column. The maximum length of crack at failure load measured from face of the column is recorded as \( R_{\text{exp}} \) each side. The maximum \( R_{\text{cal}} \) is calculated by considering maximum crack length can be produced is \( 2d \), where \( d \) is the effective depth of slab. The effective depth of slab is taken by deducted the actual thickness of slab with the size of longitudinal bar and concrete cover. In this case, size of longitudinal bar and cover is taken as 6mm and 25mm respectively. Table 5 shows the results of \( R_{\text{exp}} \) and \( R_{\text{cal}} \). The result shows that theoretically the critical perimeter, R values increased with increase of effective depth, \( d \) as shown by \( R_{\text{cal}} \). However, the critical perimeter obtained from experimental is not consistent as shown by \( R_{\text{exp}} \). Interestingly, the measured critical perimeter is producing higher values for slab S1 and S2 compared to \( R_{\text{cal}} \). It is well known that the theoretical critical perimeter of \( 2d \) is derived based on data produced from normal concrete. Therefore, it is indicated that noticeable improvement in the formation of critical perimeter for slab that produced using rubberized concrete. This due rubber aggregate particles seem to act as springs and cause a delay in widening the cracks and preventing the catastrophic failure which is usually experienced in plain concrete. This caused the cracks to appear even further than calculation. This shows that objective for this study is achieved. However, nothing was noticeable on slab S3 top surface. Only signs of local punching which due surface issues on the bottom surface. It noticeable the cracks can reach up to 250 mm from the face of the column at bottom of the slab which shows higher results than the calculated value, \( R_{\text{cal}} \).

| Specimens | Thickness (mm) | \( R_{\text{exp}} \) (mm) | \( R_{\text{cal}} \) (mm) | \( \frac{R_{\text{exp}} - R_{\text{cal}}}{R_{\text{exp}}} \) (%) |
|-----------|----------------|-----------------|-----------------|-------------------------------|
| C-S1      | 50             | 107             | 70              | 34                            |
| S1        | 50             | 280             | 70              | 75                            |
| S2        | 100            | 250             | 138             | 45                            |
| S3        | 150            | No significant crack appear | 238             | -                            |

3.3. Punching shear strength

Table 6 shows punching shear strength results obtained from experimental program. The obtained punching shear is presented as strength per unit area. The general trend is that the punching shear strength is increased as the thickness of slab increased. To assessing the reliability of obtained punching shear strength results, comparison is made between the experimental results and the strength calculated from equations of established design codes. The equations obtained from design standard used are Eurocode 2 (EC2) and American Concrete Institute (ACI). From the comparison as shown in Table 6, it indicated that both codes overestimated the punching shear strength compared to the test results. The variation of test result and equation for the EC2 is 72% and for ACI 68%. This variation is mainly contributed by the factor of compressive strength of concrete.
apart of other factors. As the derivation of the equations is based on normal concrete. And this due to the lower compressive strength of rubberized concrete which is one of the main factors in calculating the punching shear strength. Therefore, it is recommended that the existing codes is to be modified before it can use to predict the punching shear strength of rubberized concrete slab.

Table 6. Theoretical (VRd,c) and experimental (Vexp) punching shear strength of tested slabs using EC2 and ACI.

| Specimens | Vexp (kN) | VEC2 (kN) | VACI (kN) | VEC2 − Vexp (%) | VACI − Vexp (%) |
|-----------|-----------|-----------|-----------|-----------------|-----------------|
| C-S1      | 68.9      | 89.74     | 78.9      | 23              | 12.6            |
| S1        | 25        | 89.74     | 78.9      | 72              | 68              |
| S2        | 75        | 158.4     | 163       | 52.3            | 53.9            |
| S3        | 200       | 314.5     | 333.5     | 36.4            | 40              |

4. Conclusion
The works and experimental results carried out and discussed in the study have led to this conclusion:
1. The compressive strength of rubberized concrete showed a reduction in strength compared to the control mix design which is due to the reduction in compactness concrete mix.
2. Flexural and split tensile strength results showed an increase in strength compared to the normal concrete due to rubber which offered ductile failure which provides a higher capacity to absorb plastic energy under both compression and tensile loading.
3. Punching shear failure was detected regardless of the presence of rubber. The reduction in compressive strength does translate directly to the performance of the slab. This can be explained considering compressive strength one of the main factors which affects the punching shear strength. Also, the slab with rubberized concrete showed signs of ductility, unlike the normal concrete slab.
4. The critical parameters developed in the rubberized concrete flat slab was bigger compared to the calculated critical perimeter and also the control slab.
5. The existing punching shear strength equations from established codes overestimating the punching shear. The punching shear of rubberized concrete slab obtained from experimental showed lower results than the equations which indicate that the equations need to be modified in order to predict punching shear of rubberized concrete accurately.

References
[1] Elshafey A A, Rizk E, Marzouk H and Haddara M R 2011 Engineering Structures 33 5 pp 1742-1753
[2] Safiee N A and Ashour A 2017 Asian Journal of Civil Engineering (BHRC) 18 2 pp 285-309
[3] Al-Akhras N M and Smadi M M 2004 Cement and Concrete Composites 26 7 pp 821-826
[4] Gupta T, Chaudhary S and Sharma R K 2014 Construction and Building Materials 73 pp 562-574
[5] Moustafa A and Elgawady M A 2015 Construction and Building Materials 93 pp 249-256
[6] Gerges N N, Issa C A and Fawaz S A 2018 Case Studies in Construction Materials 9 e00184
[7] Onuaguluchi O and Panesar D K 2014 Journal of Cleaner Production 82 pp 125-131
[8] Nabilah A B, Noaman N M R, Nasir N A M and Safiee N A 2019 Asian Journal of Civil Engineering 20 7 pp 999-1005
[9] Siddique R and Naik T R 2004 Waste management 24 6 pp 563-569
[10] Ganjian E, Khorami M and Maghsoudi A A 2009 Construction and Building Materials 23 5 pp 1828-1836
[11] Ismail M K, Hassan A A A and AbdelAleem B H 2016 5th International Structural Specialty Conference (London: Resilient Infrastructure)