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Punching Shear Behaviour of Reinforced Concrete Flat Plate Slab using Recycled Concrete Aggregate

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ABSTRACT

The substitution of natural aggregate with recycled concrete aggregate in concrete is currently being researched to address increasing environmental and sustainability concerns. Recycled concrete aggregate is sustainable for the environment and is used in concrete production. This research addresses the experimental evaluation of recycled concrete aggregate (RCA) as a substitute for natural aggregate (NA) in interior slab-column connections. Small-scale internal slab-column connections were subjected to a concentrated load applied through the column until failure happened. The primary test variables were slab thickness and concrete type and the slabs were designed to fail in shear. All slabs had identical dimensions and a reinforcement ratio of 1%. The article provides a thorough explanation of the experimental procedure, tests, and outcomes, together with an overview of all results. The punched shear capabilities have been determined from the test results and compared with the estimated values based on the ACI code equations. The evaluation of the slabs was conducted via a comparison of load capacity, failure modes, load-deflection, concrete strain, steel strain, and cracking patterns. The test findings indicated that the presence of RCA in RC slabs resulted in only a 5 percent reduction in ultimate capacity and an enhancement in deformability compared to normal concrete (NAC) slabs. The deflection of the RCA slab was minimized by increasing its thickness; hence, its capacity was improved.

1.Introduction

Concrete is a material extensively used in structures. However, the excessive use of NA in its manufacture poses a serious risk to the preservation of our planet's natural resources. Another issue is the construction industry's massive annual waste output, which includes a significant amount of demolished concrete (Francesconi et al., 2016).

Serviceability, strength, durability, and affordability are civil engineering project assessment criteria. Performance and affordability are usually the top priorities in construction, but sustainability and environmental effects are rarely taken into account (Al-Mawed and Hamad, 2023).

Research on the incorporation of recyclable materials into concrete has been a focal point of efforts to minimize the environmental influence of the material's construction and increase its sustainability. RCAs produced from construction and demolished waste could one day replace natural aggregate (NAs) (Sahoo and Singh, 2021). Concrete can be processed, crushed, and repurposed as aggregate in the manufacture of new concretes, leading to specific varieties of green concrete in which conventional aggregates are partly or wholly replaced with RCAs, thus reducing Construction and Demolition waste (Pepe, 2015).

The use of columns rather than beams for supporting reinforced concrete flat slabs has become popular in modern construction. The positive aspects of using a flat plate design consist of quicker construction, decreased floor height, also enhanced cost-effectiveness relative to other structural methods. The connection of slab and column in flat slabs is critical, since it is susceptible to punching shear failure and brittle failure that has led to the collapse of numerous structures (Al-Mawed and Hamad, 2023).

Theodorakopoulos and Swamy (2002) stated that when a load is applied to a slab-column connection, a circular-shaped crack around the column perimeter on the tension zone of the slab, new lateral and diagonal flexural cracks, and an inclined shear crack near the slab's mid-depth are formed. These cracks eventually lead to the concrete's compression zone. In the last stage, the inclined crack is slowed down by the compression zone above it, which is close to the column face, and the tension steel dowel action. Cracks tend to move toward compression zones and tension reinforcements as stresses increase. Especially when using appropriate reinforcing percentages, this is the point where the slab tension steel next to the column offers direction. When the column is close to yielding in the compression region, punched shear failure happens.

Assuming that the shear capacity is affected by the concrete in a way comparable to that which causes inclined splitting, the concrete is considered to have contributed to the shear capacity through resistance across the concrete compressive area, aggregate interlock, and dowel action (ACI 318-25) and (Reba and Aure, 2022). Ioannides and Korovesis (1990) and Reba and Aure (2022) stated that a method for stress transmission in cracked concrete is the interlocking of aggregates. Aggregate interlock is a natural process that efficiently transfers loads across discontinuities, including joints and fractures, in plain or reinforced Portland cement concrete.

The overall interlock is influenced by rough fracture boundaries that restrict sliding by interlocking aggregate particles across the fracture. The implemented fracture mechanics may induce substantial slip displacement at crack interfaces when concrete fails under tensile load. Enhanced slip at fracture surfaces results in stresses transmitting shear and normal load across aggregate interlocks. The crack spacing and the relative movement of the fracture surfaces are the principal characteristics affecting the impact of aggregate interlock on shear resistance. Aggregate interlock is affected by variables related to concrete, such as concrete strength, and aggregate size and type (Reba and Aure, 2022, Jayasinghe et al., 2022). El Zareef et al. (2023) found that aggregates with a higher angularity had better long-term performance and greater aggregate interlock impact. Since the aggregate interlock effect is larger when the slab thickness is increased, the final punching load is noticeably higher than when the reinforcement ratio is increased. According to Ju et al. (2021), recycled coarse aggregates have poor qualities that diminish shear resistance and have a negative impact on aggregate interlock. A weak aggregate interlock mechanism explains the drop in shear capacity. Recycled concrete leaves a layer of the original adhesive on the coarse aggregate. An extra contact layer reduces the capability of aggregate interlocking.

The resistance of a slab to punched shear stress depends on a number of factors, as stated by Theodorakopoulos and Swamy (2002). All the following must be taken into account: concrete strength, column geometry, lateral restrictions, shear strength to flexural strength ratio, slab effective depth to column size ratio, and several others.

(Ahmed and Aziz (2015), Al-Mawed and Hamad (2023), Alam et al. (2009), Ahmed and Aziz (2011), Aziz and Ahmed (2009), Ioannides and Korovesis (1990)) and Reba and Aure (2022) indicated that the thickness of the slab significantly influences the ultimate punching shear strength; a drop in the ratio (l/t or ln/d) results in an increase in the ultimate load capacity. Numerous studies have investigated the efficacy of RCA. The advantages of RCA from construction demolished waste comprise a reduction in the use of natural resources and a large decrease in the storage of waste materials at landfills, yielding substantial environmental benefits. The investigation indicated that the performance and strength of the slab are influenced by RCA due to the physical and mechanical characteristics of the aggregates (Leelatanon et al., 2022, Sahoo and Singh, 2021, Rao et al., 2012, Mahmoud et al., 2018, Francesconi et al., 2016).

Leelatanon et al. (2022) evaluated the influence of RCA on the punching shear strength of slab-column connections across 10 slabs. Replacement ratios of 25%, 50%, 75%, and 100% were among the criteria, along with flexural reinforcement ratios of 0.8% and 1.5%. Compressive strength of the specimen was less than 30 MPa. According to the research, using 100% RCA instead of NA at flexural reinforcing ratios of ρ = 1.5% and 0.8% resulted in a 6.5% and 9% drop, respectively, in the punched shear strength of the RAC slab.

Moreover, (Sahoo and Singh, 2021) investigated the punching shear strength of slab by varying concrete compressive strength and the volumetric substitute quantities of coarse RCA (0%, 50%, and 100%). The test outcomes indicated that an increase in the proportion of RCA led to a drop in punching shear strength. The concrete compressive strength greatly influenced the test results. In comparison with normal, medium and high strength concrete containing 50% RCA showed rises in punching of 4.6% and 6.6%, respectively. The punching shear strength of RCA with 100% use rose by 4% and 6.4%, respectively. Rao et al. (2012) assessed fifteen specimens of RAC slabs and three NAC slabs for their punching shear strength. The support condition was simply supported. This study used replacement percentages of NA with RCA at levels of 0%, 20%, 40%, 60%, 80%, and 100%. The results achieved in this research indicated that the mechanical properties of concrete, namely compressive strength and splitting tensile strength, decreased as the amount of RCA increased. The compressive strength decreased by 23% when 100% RCA was used in place of NA in concrete. The outcomes have indicated that an increase in the substitution of NA with RCA correlates with a reduction in the first crack and ultimate load, deflection at ultimate load, and stiffness degradation, resulting in premature cracking.

Additionally, (Mahmoud et al., 2018) investigated the impact of two nominal aggregate sizes 12.5 mm and 25mm, and various substitution ratios (0%, 30%, 60%, and 100%). The targeted compressive strength of the concrete was 35 MPa. Eight simple support square slabs were evaluated. The findings indicated that the failure mechanism of all specimens was punching shear failure, shown by a reduction in compressive strength and splitting tensile strength as the percentage ratio of RCA increased. The use of 25 mm aggregate size enhanced both splitting tensile and compressive strength. In the slab testing, the first cracking load and ultimate load diminished by 25% and 24% with the use of 100% RCA of 25 mm, and dropped by 26% and 22.5% with 100% RCA at 12.5 mm, respectively. The deflection at ultimate load reduced by 23% with the usage of 100% RCA 25 mm and by 26% with 100% RCA

12.5 mm, indicating that the smaller aggregate size of RCA exhibits better performance to minimize deflection. (Francesconi et al., 2016) examined the impact of several percentages (0%, 30%, 50%, 80%, and 100%) of coarse RCA. The mechanical characteristics of concrete, including compressive strength, modulus of elasticity and splitting tensile strength, decreased as the amount of RCA increased. The test results of the slabs indicated that an increase in the percentage of RCA led to a slight increase in both the first fracture load and the ultimate load, and displacement similarly increased. The difference in deflection at ultimate load between RCA and NA slabs reaches 15% at a replacement ratio of 50%, with a load differential of 2.53 kN.

Several studies have examined the efficacy of increasing thickness as a strengthening approach to slab-column connections. The investigations indicated that increasing slab thickness improves punching shear resistance by raising the effective depth, widening the critical shear perimeter, and enhancing the overall stiffness of the slab-column connection (Ahmed and Aziz, 2015, Al-Mawed and Hamad, 2023, Lampropoulos et al., 2023, El Zareef et al., 2023, Alam et al., 2009).

Ahmed and Aziz (2015) examined the simply supported reinforced concrete flat plate using Ultra High Performance Concrete with a slab thickness ranging from 30 to 50 mm. The ultimate punching load was enhanced by 17.2% and 76.7% when the slab thickness was raised from 30 mm to 40 mm and 50 mm, correspondingly, whereas the deflection at ultimate load dropped from 60mm to 21mm with an increase in slab thickness from 30mm to 40mm.

Al-Mawed and Hamad (2023) examined the impact of thickness on punching shear strength, a variable analyzed in this study. The findings indicated that initial stiffness and ultimate load of the slab rose by 46.9% and 52.4%, respectively, while deflection at ultimate load reduced by 2.81 mm.

2.Aim and novelty of research

2.1Aim of the research

This research objective is to evaluate the punching shear behavior of reinforced concrete slabs as a function of slab thickness and concrete type (normal concrete and RCA concrete). In terms of load-deflection response, failure modes, stiffness, and ultimate shear capacity, the research compares the performance of RAC slabs with that of ordinary normal aggregate concrete (NAC) slabs, also three separate slab thicknesses that include RCA. The optimum RCA content was determined through preliminary trial mixes and applied consistently across slabs of varying thickness.

2.2 Scientific novelty

This study examines how RCA incorporation and slab thickness variation affect punching shear behavior, unlike previous studies that compared RCA and normal concrete in typical slab–column specimens with constant dimensions. The research examines how structural size and RCA effect shear capacity, fracture pattern, and failure mode by evaluating slabs of varying thicknesses made of RCA concrete. This combined parametric evaluation has not been previously reported in the literature and thus represents the main contribution of this work.

3.Experimental Program

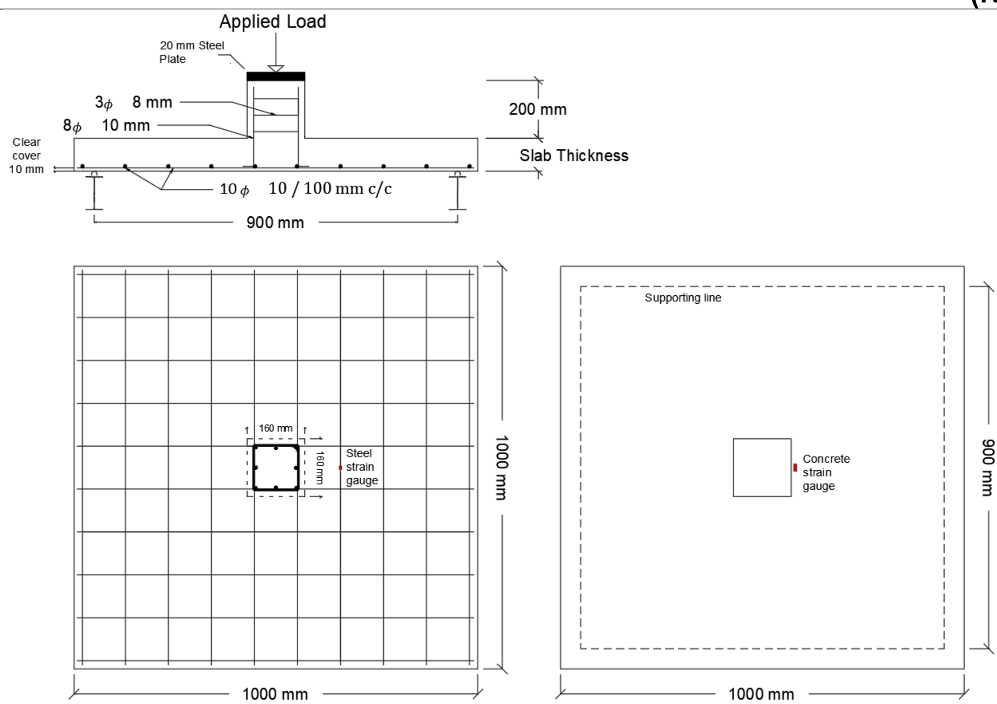
The geometry, construction details, and loading arrangements of all test specimens were identical. The objective of the investigation was not to determine the exact numerical values of the test results for the different specimens. The results comparing the concrete type specimens to those with greater thickness and the effects of various factors were the most significant.

3.1Test Specimens and Parameters

Four specimens of internal reinforced concrete slab-columns, each measuring 1000 × 1000 mm, with a central column stub of 160 × 160 mm and extending 200 mm from the surface of the slab, were evaluated by applying load through hydraulic jack testing equipment with a capacity of 2500 kN. The specimen geometry conforms to the dimensional limits (opening) of the testing apparatus. Figure1 illustrates the standard dimensions of the specimen. The specimen elements were designed to examine the influence of slab thickness and concrete type on punching shear strength of internal slab-column connection. The slab thicknesses of 60, 80, and 100 mm were the main variables in the investigations. Assuming the supports are lines of contra-flexure, the chosen slab thicknesses correspond to span length-to-depth ratios of 15, 11.25, and 9, correspondingly. Separating the specimens into two groups according to the examined parameter was the first step. Group G1, consisting of three slabs, varied in thickness to investigate the influence of slab thickness on punching shear behavior. Group G2, consisting of two slabs, has identical geometry but used different concrete types (normal concrete vs RCA concrete), which allows an independent evaluation of the concrete type's influence. This classification clarifies the experimental design and separates the impacts of the examined variables. For the purpose of comparing the impacts of different slab thicknesses and types of concrete, specimen T2/SC1 served as a control specimen as it was included in both groups of experiments. A notation is assigned to each specimen. The test parameters are summarized in Table 1.

Table 1: Design of the tested specimens

Group No.	Specimen No.	Slab size (Length* Width) (mm)	Slab thickness (mm)	Column		Type of concrete
				Shape	Size (mm)	
G1	T1		60			
	T2/SC1	1000*1000	80	Square	160*160	**Concrete containing recycled concrete aggregate (RAC)**
	T3		100			
G2	OC1		80	Square	160*160	**Ordinary Concrete (NAC)**



(a) **(b)**

Figure1: Illustration of the typical details of tested specimens (a) reinforcement arrangement and location of steel strain gauge, (b) concrete strain gauge and the boundary condition

3.2.Preparation of materials and testing Specimens

3.2.1.Recycled concrete aggregate (RCA)

Random elements of the concrete slabs and box girders from the previous experiment have been chosen and crushed for the purpose of the production of recycled concrete aggregate. The concrete was more than two years old, and the strength of the elements ranged from 39 to 120 MPa. The aggregate was first sieved using a shaker, followed by the mixing of single-sized aggregates in accordance with the grading design that complies with the standard specifications outlined in ASTM C33, to produce well-graded coarse and fine aggregates (RCA and NA). The NA and RCA used in this investigation had a maximum size of about 19 mm. The specific gravity and water absorption of the coarse recycled concrete aggregate were 2.33 and 5.885%, respectively, while the comparable values for natural coarse aggregate were 2.75 and 0.685%. The aggregates used in this investigation were soaked for 24 hours, subsequently rinsed with water, and then employed in the concrete mix in a saturated surface dry condition.

3.2.2.Concrete

High-performance concrete (HPC) was used consistently throughout the experimentation process. The concrete mix design was determined using trial mixes to identify the optimal amount of RCA as a replacement for NA. The concrete used for three slabs included both RCA and NA named (RAC slab), while one slab consisted of only NA named (NAC slab).

Researchers Tran et al. (2021) and Abd Elhakam et al. (2012) tested various amounts of coarse RCA replacement in concrete. They found that a 25% replacement ratio produced results that were similar to regular concrete in terms of compressive strength, so for this experiment both fine and coarse RCA is include, for this purpose a trail mix was done by using 25% of coarse RCA and different replacement level of fine RCA (0%, 25%, 50%, 75% and 100%) , the results of compressive strength was (66.5, 66.7, 65.5, 73,and 58.7) MPa respectively.

The proportion of coarse and fine RCA determined from experimental mixes for slab casting was 25% coarse RCA and 75% fine RCA. The concrete components included Portland cement Type I, micro silica, superplasticizer admixture (Hyperplast PC 175* from Don Construction Products Ltd. (DCP)), well-graded sand, RCA, and NA. In order for both kinds of concrete to reach a compressive strength greater than 40 MPa, HPC is designed following ACI PRC-211.1-22.

The weights of materials for the concrete mix in kilograms per cubic meter are presented in Table 2. Each slab's concrete was produced and cast separately, with each batch of concrete designed to the specific quantity needed for each slab. According to the calculation of ACI PRC-211.1-22, the quantity of cement to be added to mixture were 475 kg/m^3. The W/C ratio was 0.38. A dose of 0.75% per weight of cement quantity of Hyperplast PC175* was included to enhance the consistency of the concrete mix. To make the HPC stronger and last longer, a dosage of Densified Micro silica (MegaAdd MS(D)) equal to 8% of the cement quantity was added to it. The superplasticizer complied with ASTM C494. In compliance with ASTM C39/C39M-14, the compressive strength of the concrete in each mixture was evaluated using 150×300 mm standard cylinders and 150×150×150 mm cubes, while the flexural strength was evaluated per (ASTM_C78/C78M-22, 2022) using a standard prism measuring 75×75×380 mm. In the durability test (BS EN 12390-8:2019), the water penetration depth was 18 mm for mix containing RCA and 11 mm for the mix with natural aggregate (NA) only. The tests were conducted on 150 x 150 x150 mm cube samples.

The specimens, including slabs, cubes, cylinders, and prisms, were fabricated using a laboratory mixer, and the specimens together with their respective cylinders and cubes were cured using a water-based curing agent (Seatseal 22 from DCP) for 56 days before testing, rather than using water. Figure 2 shows the steps of preparing of mold, casting, and curing of specimen.

Table 2: Mix proportion of slabs

Group	Aggregate content (Kg/m^3)		Cement content (Kg/m^3)	Water content (Kg/m^3)	W/c	Micro silica content	Superplasticizer
	Coarse Aggregate	Fine Aggregate					

	Natural	Recycled	Natural (1.18 to 0.15 mm)	Natural (4.75&2.36 mm)	Recycled (4.75&2.36 mm)					
G1	717.25	237.5	655.5	28.5	85.5	437	180.5	0.38	38	3.6
G2	954.75	0	655.5	114	0	437	180.5	0.38	38	3.6

(Ahmed and Aziz, 2015Ahmed and Aziz, 2015)

Figure 2: Slab's casting configuration (a) slump of mix, (b) preparing mold, (c) casted sample, and (d) spring curing material

The results of fresh concrete in Table 3 indicate that the slump of all mixes exceeds 20 cm, due to the use of a high-range water reducer (HRWR). The HRWR is chosen since it is advised for HPC, resulting in an increase in the durability and strength of the concrete. Reduction of slump of G1 compared to 2 returns to effect of shape of the aggregate particles ion the workability of the concrete), and the reduction in density of G1 compared to G2 is related to the use of RCA, which has a lower weight than NA, this is due to the recycled concrete aggregate (RCA) has a lower density than natural aggregate, resulting in RCA concrete being around 7–17% lighter than ordinary concrete according to (McNeil and Kang, 2013).

The compressive strength of cylinder specimens from all mixtures has exceeded the designed compressive strength of 40 MPa, and the test was conducted according to ASTM C39/C39M-14. The compressive strength is increased by 111% to 150% of the designed compressive strength. The design mix for group 1 is chosen from several trial mixes, leading to the selection of the optimal proportion of RCA. When comparing the strength of G1 and G2, a little variance in strength is seen because of the casting of each mix alone.

Moreover, McNeil and Kang (2013) mentioned that the modulus of rupture, an indicator of flexural strength, and the modulus of elasticity, an indicator of concrete stiffness, are often estimated based on compressive strength; however, these correlations do not accurately characterize RCA concrete compared to NA concrete. The examination of prisms and cylinders assessed each modulus and the influence of RCA on these concrete qualities.

The calculation of flexural strength is essential to evaluating concrete's ability to withstand bending and cracking development. The high-strength concrete mix needs to have a flexural strength ranging from 5 to 7 MPa, and the test results confirmed this strength. The findings indicate that concrete T1 presented more strength compared to OC1; nevertheless, OC1 had a greater flexural strength, indicating that RCA contributed to a reduction in flexural strength by about 2%, according to the test results.

Upon comparing the test results with the ACI 318 equation $4700\sqrt{f'c}$, the allowable difference between the test results and the code equation is ± 10%. The differences between the test and ACI equation are within the acceptable range.

Table 3: Results of mechanical properties of concrete after 56 day

Group	Specimen No.	Fresh concrete property		Compressive strength (MPa)		Flexural Strength (MPa)	Modulus of elasticity (MPa)
		Slump (cm)	Density (kg/m³)	Cylinder	Cube		
G1	T1	22.5	2444.4	62.28	67.1	6.89	36406.6
	T2/SC1	23	2381.6	44.16	57.5	5.82	33475.3
	T3	24	2389.6	51.10	64.8	6.04	33045.0
G2	OC 1	24.5	2426.9	50.96	60.1	7.00	35165.5

3.2.3.Reinforced steel

All specimen slabs were reinforced with 10 mm dia./100 mm c/c (Grade 60 deformed bars) in both directions, providing a 1% reinforcement ratio. The average effective depth to the centers of the two reinforcing layers was 40 mm for the T1 specimen, 60 mm for the T2/SC1 and OC1 specimens, and 80 mm for the T3 specimen. Eight deformed vertical bars, each with a diameter of 10 mm, were positioned at the column stub for all specimens. Three 8 mm diameter ties, spaced 50 mm apart, connected the vertical column bars. The standard dimensions and steel reinforcement arrangement of the test specimens are shown in Figure 1.

Three samples of each 10 mm and 8 mm bars were evaluated following ASTM C615/C615M-22. Table 4 shows the average yield and ultimate strength values above 420 MPa and 550 MPa, respectively, with elongation values exceeding 17.5 mm and 20 mm, respectively.

Table 4: Properties of reinforced steel bars

Diameter of bar (mm)	Yield strength (MPa)	Ultimate strength (MPa)	Elongation %
8	424	644.7	20.5
10	467.6	695.5	22

3.3Test Setup and Instrumentation

Figure 3 shows the procedure for testing an

inverted specimen under load, which included transferring the load to the specimen via the column stub and then gradually increasing the force until failure. A universal computerized apparatus subjected all slab specimens to a similar ring load at a predicted average rate of 2 kN/min for evaluation.
The slabs were attached to a steel frame, with a 50 mm steel bar placed on the I-section, connecting to the frame on all four sides to provide a simple support condition; the corners of the slab were allowed to rise upon load application. A steel cap was positioned on top of the column stub to uniformly distribute the load rigidly, ensuring the column would not fail prior to the slab. The test measures included the applied load, slab deflection, and strain in both concrete and steel.
Linear variable differential transformers (LVDTs) were positioned at the bottom of the slab of the specimen being examined to collect deflection measurements at the middle of the slab. Two strain gauges were attached, one at the midpoint of the steel bar as its position is shown in Figure 1, the electrical strain gauge was 6 mm, and its model (FLAB-6-11-3LJC-F) was for steel bars. A different electrical strain gauge of 60 mm and its model (PL-60-11-3LJC-F) used for concrete strain was positioned at the upper section of the slab, at a distance of d/2 from the column stub face, as displayed in Figure 1. A computer and data logger system kept track on the applied load, LVDT, and strain gauge values.

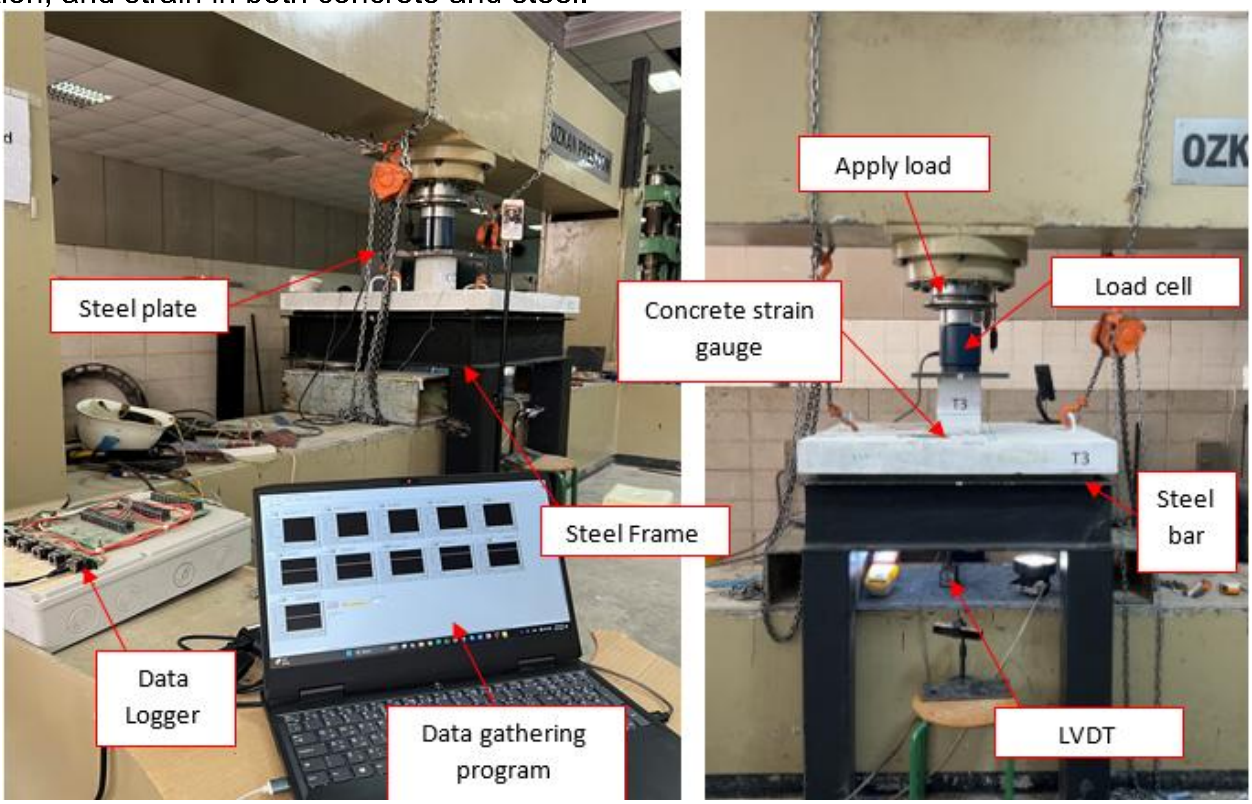


Figure 3: Test setup

4.Results and Discussion

4.1.Load–Deflection Response

The punching shear behavior of flat plate is significantly influenced by their dimensions. This investigation included testing sub-scale slabs due to experimental limitations. Consequently, the assessed shear strength and load–deflection characteristics may vary from those of full-scale slabs. However, the results obtained clarify the impact of slab thickness and concrete type.
Figure 4 shows a comparison of the load relative deflection curves for all specimens that experienced punching shear failure. Loads are shown in unnormalized form to accurately represent the performance of slabs with varying thicknesses and concrete type, including the

combined impact of concrete strength, aggregate type, and member shape as experimentally found. The configuration of load–deflection curves can be utilized to figure out the linear stiffness of slabs until the beginning of the initial crack; subsequently, as the applied load increases beyond this point, a nonlinear load-deflection response follows due to the growth of additional cracks at the slab's bottom, which also spread towards the slab's edges.

Table 5 summarizes the measurements of load and deflections at first cracking and at ultimate loads. All specimens showed rapid punched shear failures that included a rapid reduction in load, followed by a rise in resistance as deflections increased.

Figure 4(A) illustrates the impact of increasing the slab thickness. The thickness of the T2/SC1 specimen satisfies the minimal requirement specified in ACI 318. The load-deflection response of control Specimen T2/SC1 was lower to that of Specimen T3, which had greater thickness. Specimen T3 showed 37% and 111.5% higher punching shear resistance relative to Specimens T2/SC1 and T1, respectively, while its deflection was reduced by 28% and 25% compared to Specimens T2/SC1 and T1, respectively. The enhancement in strength comes from the advantageous effects of increased thickness, which improves stress distribution across cracks and improves resistance to cracking.

The evaluation indicates that OC1 (NAC slab) has a punching resistance that exceeds T2/SC1 (RAC slab) by 5%, while showing a deflection reduction of 20% as shown in Figure 4(B). Despite the lack of direct examination of ITZ quality and residual mortar content, the load-deflection behavior demonstrated that the cleaned and pre-soaked RCA enhanced bonding and surface quality. It seems that the aggregate interlock and overall slab performance may be affected by the intrinsic microstructural characteristics of RCA, since slabs containing RCA demonstrated a slightly reduced stiffness compared to natural concrete slabs.

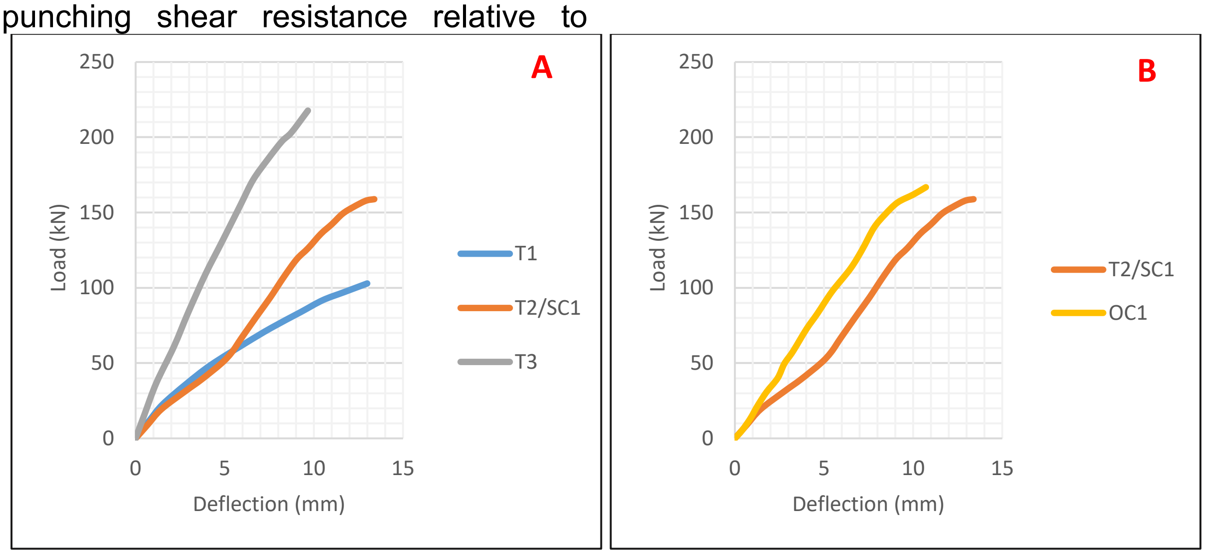


Figure 4: Load–deflection curves of the specimens (A) Group 1 and (B) Group 2

Table 5: Experimental results (punching load and deflection) at first crack and ultimate load

Group	Specimen No.	Experimental results			
		P_{crack} (kN)	δ_{crack} (mm)	P_u (kN)	δ_{max} (mm)
G1	T1	19.4	1.34	102.9	13.0
	T2/SC1	18.0	1.6	158.9	13.4
	T3	39.3	1.4	217.6	9.7
G2	OC 1	30.0	1.4	166.9	10.7

4.2.Stiffness of slab

The stiffness of a structure is the ratio of force to displacement or deflection. Stiffness may be determined between two points on the load-deflection curve (Falih et al., 2022); a higher stiffness value signifies more resistance to deformation.

Specimens exhibit bilinear behavior up to the maximum load, with two separate phases: the first step of reaction is defined the initial stiffness of the uncracked slab represents the early loading stage, whereas the subsequent phase is indicated by a decrease in resulting from the formation of tensile flexural fractures (Al-Mawed and Hamad, 2023). Muttoni and Fernández (2008) stated that stiffness before cracking relies on strength of concrete; however, after cracking relies on the strength of steel reinforcement .

Table 5 indicated that the within G1, specimen T3 exhibited the greatest initial stiffness, related to its higher thickness, requiring an additional force to cause the first crack, also the lower deflection at the first crack indicated greater initial stiffness. In the compression of OC1 (NAC slab) with T2/SC1 (RAC slab), the initial stiffness of the NAC slab is superior, as it required a greater load for the first crack to appear; the little deflection at the first crack further supports this observation.

The load-deflection response of the slabs shown in Figure 4 indicated that increasing the thickness of slab T3 by 25% relative to T2/SC1 influenced the ultimate stiffness of the slabs, as T3 required a greater load to fail, and the increased thickness reduced the final deflection of the slab. The lowest stiffness of T1 was associated with a reduced thickness; specifically, T1's thickness reduced by 25% compared to T2/SC1, resulting in diminished ultimate stiffness and a loss of ability to withstand greater loads in comparison to T2/SC1.

Comparing T2/SC1 (RAC slab) and OC1 (NAC slab), it is evident that the deflection at ultimate load is greater in T2/SC1 than in OC1.

Nevertheless, the rigidity of T2/SC1 and OC1 is somewhat similar. A possible reason for the slight decrease in stiffness of T2/SC1 is the weak bond between RCA and cement, as this problem in normal concrete is not obvious. However, a possible explanation for the owing good stiffness of T2/SC1 is due to higher aggregate interlock in RCA slab, since recycled concrete aggregate (RCA) has more angularity than natural aggregate (NA), hence enhancing the stiffness.

4.3Impact of the Span-to-Depth Ratio

According to Table 5, increasing the slab thickness from 80 mm (T2/SC1) to 100 mm (T3) reduced the span-to-depth ratio from 11.25 to 9, which in turn improved the specimens' ultimate load capacity and initial load-deflection stiffness. Between T2/SC1 and T1, the thickness decreased from 80 mm (T2/SC1) to 60 mm (T1), which is below the minimum thickness specified by ACI. The maximum load capacity and stiffness were both reduced as a consequence of increasing the span-to-depth ratio from 11.25 to 15. In Figure4, it could be seen that how the control specimens react to different slab thicknesses in terms of load-deflection. Specimen T3 has a 37% higher maximum load capacity than specimen T2/SC1.

4.4.Steel and concrete strain

Figures 5 and 6 illustrate the typical load versus strain curves obtained from the concrete and steel bars of the tested specimens; the relationship is characterized as bilinear, similar to the previously described load–deflection response. Prior to the fracture of the slab specimen, minimal strain was noticed in both the concrete and steel bars, and the curve indicated a slightly high slope. As the applied load grew, tensile fractures in the concrete slab developed, resulting in a reduction in the slope of the curve and a nearly linear behavior in the load-strain response of the concrete and steel bar until the specimen failed.

All specimens generally show maximum strains in concrete that are less than 0.003 (ACI 318) at the maximum load. Specimens with 100 mm (T3) slab thickness show reduced concrete strains at ultimate load compared to specimens with 80 mm (T2/SC1) and 60 mm (T1) slab thicknesses.

This phenomenon can be attributed to the increased effective depth in T3, which indicates enhanced stiffness, more effective resistance to deformation, and reduced deflections under similar loads. The differences in concrete strength are responsible for the slight difference in strain between T2/SC1 and OC1. Table 6 showed the concrete stain of slabs at cracking load and ultimate load.

The percentage of steel reinforcement was uniform, and a strain gauge was positioned similarly on all specimens. At peak load, the highest steel strains of all specimens passed 0.00207 (ACI 318), which is considered the yield strain of steel, indicating that the steel was fully engaged in resisting the imposed force. The yielding of the steel reinforcement happened in all slabs prior to attaining the maximal punching load, a behavior that enhanced the ductility and energy dissipation capability of the slabs. The components contributing to the rise in strain were the reinforcement ratio, the applied load, the slab thickness, and stiffness. Table 7 showed the steel stain of slabs at cracking load and ultimate load.

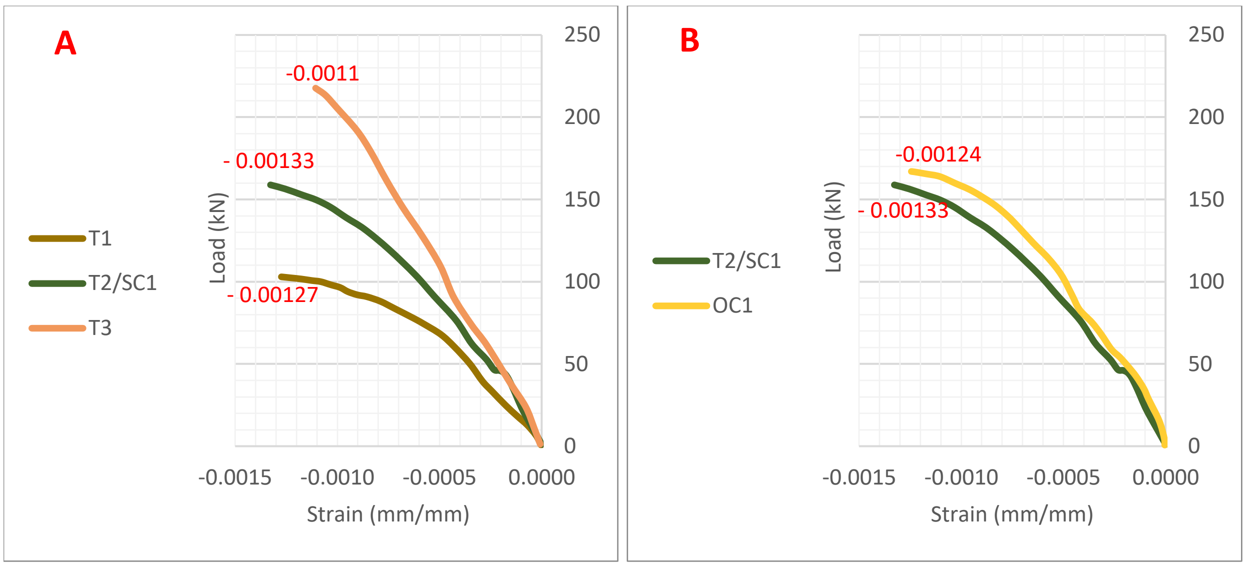


Figure 5: Load versus concrete strain response for (A) Group 1 and (B) Group 2

Table 6: Strain of concrete

Group	**Specimen No.**	**Experimental results**			
		P_{crack} **(kN)**	$\varepsilon_{c,\,crack}$ **(mm/mm)**	P_u **(kN)**	$\varepsilon_{c,\,max}$ **(mm/mm)**
G1	T1	19.4	-0.0001312	102.9	-0.0012744
	T2/SC1	18.0	-0.0000648	158.9	-0.0013267
	T3	39.3	-0.0001574	217.6	-0.0011058
G2	OC 1	30.0	-0.0000860	166.9	-0.0012436

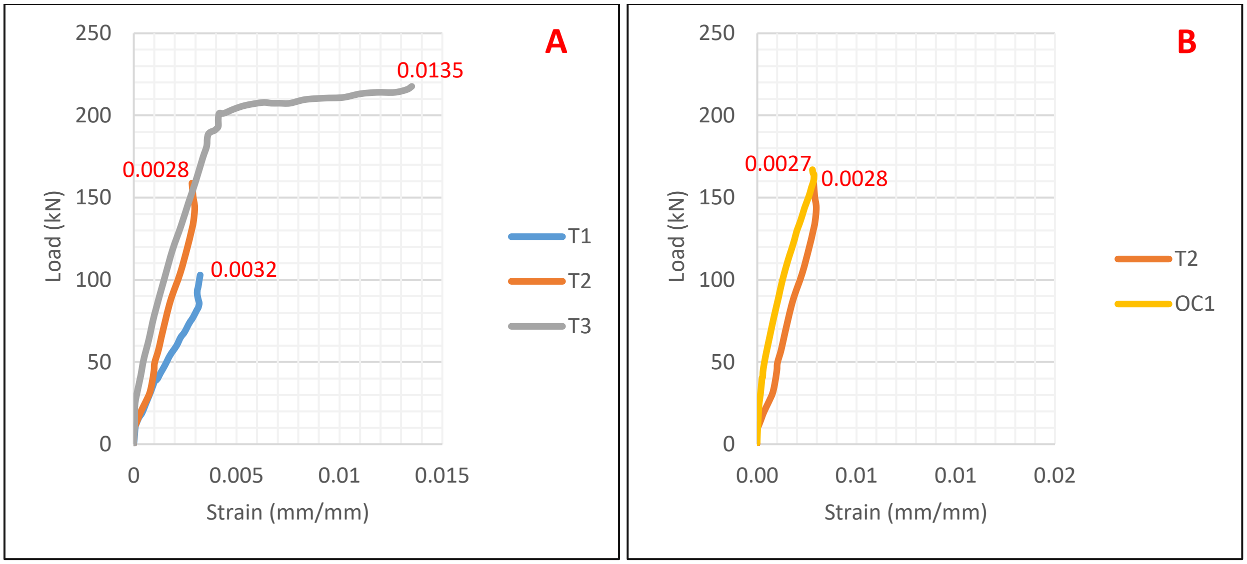


Figure 6: Load versus steel strain response for (A) Group 1 and (B) Group 2

Table 7: Strain of steel

Group	Specimen No.	Experimental results			
		P_{crack} (kN)	$\varepsilon_{s,\ crack}$ (mm)	P_u (kN)	$\varepsilon_{s,\ max}$ (mm)
	T1	19.4	0.0003991	102.9	0.0032289
G1	T2/SC1	18.0	0.000225973	158.9	0.002838
	T3	39.3	0.0003097	217.6	0.0135169
G2	OC 1	30.0	0.0001439	166.9	0.0027896

4.5.Comparison of results from experiments with ACI equations.

For the purpose of determining how well-designed codes predict the punched shear strength of slab-column connectors. It is possible to compare the predicted shear from the ACI 318-25 equation with the experimental punching shear.

ACI 318-25 has three expressions for nominal shear strength, expressed as

$$Vc = 0.33\, \lambda s\, \lambda \sqrt{f'c}\, \text{bo d} \quad \text{....... (a)}$$

$$Vc = \left(0.17 + \frac{0.33}{\beta}\right) \lambda s\, \lambda \sqrt{f'c}\, \text{bo d} \quad \text{....... (b)}$$

$$Vc = \left(0.17 + \frac{0.083\, \alpha s\, d}{bo}\right) \lambda s\, \lambda \sqrt{f'c}\, \text{bo d} \quad \text{....... (c)}$$

The term $\sqrt{f'c}$ refers to the cylinder compressive strength of the used concrete. The variable "b_0" represents the circumference of the critical section situated 0.5d_{av} from the column faces, "d" is the effective depth of slab, "αs" refer to critical sections with a continuous slab, "β" is the ratio of long to short sides of the column, "λs" is the size effect factor, and "λ" is modification factor for lightweight concrete, the punching shear strengths are calculated without taking material safety considerations into account and without considering the contents of the RCA.

The Slab specimen T3, with higher concrete strength and larger thickness compared to Slab T2/SC1, gained a 36.9% improvement in punching shear capacity. The improvement is recognized to improve compression resistance and greater effective depth, both of which raise the slab's capacity for resisting punching shear failure. While specimen T1 has a higher strength and smaller thickness compared to T2/SC1, the results showed that the lower thickness decreased the punching shear capacity of T1 by 35.2%, it means that the thickness has higher effect on punching shear capacity compare to concrete strength.

There is a 5% difference in punching shear strength between T2/SC1 (RAC slab) and OC1 (NAC slab). The resistance of OC1 is slightly higher due to higher compressive strength, considering that both slabs have identical geometry.

Table 8 displays the results of the examination of the punching shear strength ratios, which revealed differences between the experimental value and predicted punching shear strength from ACI.

The experimental findings show that the current design equations provide an acceptable estimate of punching shear strength for RCA concrete, which is in reasonable agreement with the ACI 318 standards; nonetheless, there was a little decrease in punching strength. Therefore, it seems that the present ACI 318 equations may still be utilized for design purposes, so long as the real mechanical characteristics of RCA concrete are included. The results do not indicate an immediate modification of ACI 318 requirements but highlight the need for more experimental data and possible future modifications in the code commentary to address RCA's impact on shear behavior.

Table 8: Comparison between experimental and predicted results.

Group	Specimen No.	f'c	Experimental results				Predicted shear resistance according to ACI 318 equation					
			V_{crack} (kN)	δ_{crack} (mm)	V_u (kN)	δ_{max} (mm)	V_{ACI-a}	V_u/V_{ACI-a}	V_{ACI-b}	V_u/V_{ACI-b}	V_{ACI-c}	V_u/V_{ACI-c}
G1	T1	62.279	19.4	1.34	102.9	13.0	82.86	1.24	124.3	0.83	90.75	1.13
	T2/SC1	44.161	18.0	1.6	158.9	13.4	107	1.48	160.5	0.99	134.9	1.18
	T3	51.097	39.3	1.4	217.6	9.7	167.3	1.30	251	0.87	228.4	0.95
G2	OC 1	50.96	30.0	1.4	166.9	10.7	105	1.59	172.4	0.97	144.9	1.15

4.6.Failure Modes

Punching shear failure was one of the failure modes observed. There were obvious indications of punching shear failure in every specimen. The failures also showed signs of two-way shear because the cracks developed in two perpendicular directions. The failure pattern, which showed conical cracks around the column, and the overall load-deflection response indicate that punching shear, not flexural failure, was the most common mode. At every stage of the testing procedure, cameras captured images of the specimens to reveal their failure mechanism and the pattern of cracks on the tension side. As shown in Figure 7, the ductile failure mode began with flexural yield lines at the corners of the columns and spread to the edges of the slab. Then, punching shear cracks, with a generally square-shaped crack matching the geometry of the columns, appeared.

Observations after the failure of the tension side reveal that as the slab thickness of increases, the distance between the major failure crack and the column stub also increases, indicating an expansion of the failure region in comparison to slabs with thinner thicknesses T1 and T2/SC1.

T2/SC1 is a control specimen that matches OC1 in size and thickness; the only difference is based on the type of concrete used. The failure plane of OC1 is larger than that of T2/SC1.

Regarding the development of cracks around the column on the compression zone of the slab, for specimen OC1 no cracks have been observed, while cracks have formed for the samples that contained RCA.

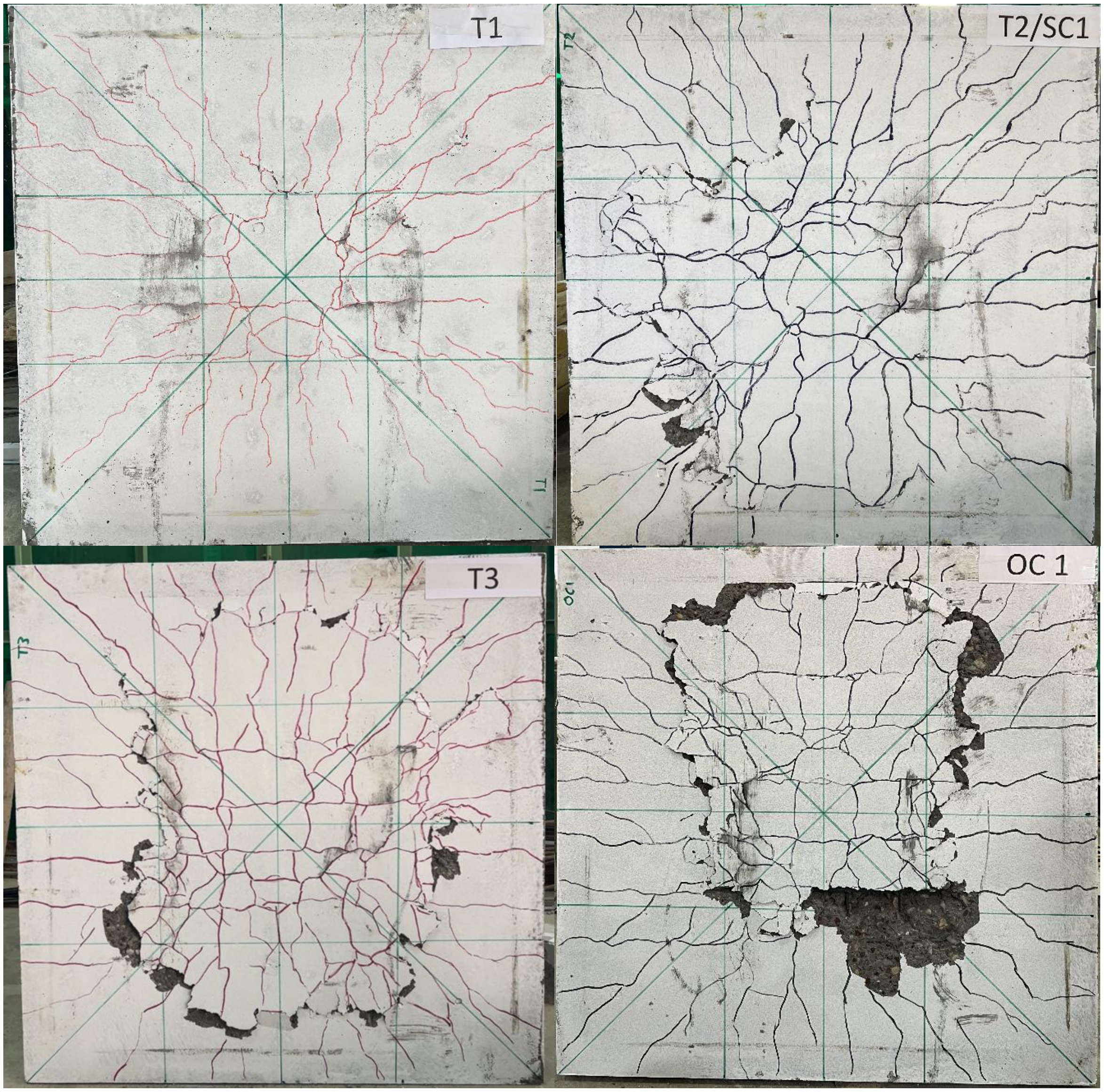


Figure7: Punching shear failure pattern in the bottom areas of slabs

5.Conclusion

This study investigated using slab thickness parameter to enhance the punching shear resistance of slab-column connections and examined the effect of partially replacing of natural aggregate with recycled concrete aggregate (RCA). Four small-scale internal slab-column specimens were tested. From the results of the research, the following conclusions may be drawn:

- Slab thickness increase from 80 mm to 100 mm improved initial stiffness under load-deflection and final load capacity significantly. This is because the span-to-depth ratio drops from 30 to 24. Reducing the thickness also reduced the slab's ultimate capacity. Slab stiffness and capacity are both affected noticeably by reducing the slab thickness.
- Slabs containing recycled concrete aggregate had greater deflection. The deflection at the ultimate load of T2/SC1 (RAC Slab) was 25.4% more than that of OC1 (NAC Slab).
- The use of RCA in concrete mixes resulted in the first fracture appearing earlier than in slabs that consisted of NAC. The cracking and ultimate load capacity of slabs subjected to punching shear decreased with the addition of RCA into the mixtures. The reduction ratio was 60% and 5% in the cracking loads s and ultimate loads, respectively.

- The reduced slab thickness of T1 causes its initial stiffness to be lower than that of T2/SC1. Conversely, the increased thickness of T3 resulted in enhanced rigidity of the slab and a reduction in deflection. The use of RCA concrete resulted in a slight reduction in stiffness and an increase in deflection. The influence of aggregate interlock in recycled concrete aggregate (RCA) assists the slab in maintaining better rigidity.
- The predicted shear resistance per ACI 318 closely corresponds with the experimental result.
- Recycled concrete aggregate increases water penetration, with conventional concrete having 11 mm penetration and RCA concrete having 18 mm.
- The cracking behavior for both concrete types (with and without RCA) is mostly similar; however, the cracks in T1 are fewer in quantity and considerably smaller due to the early failure of the slab.
- This study is limited by the small sample size of four slabs, which restricts statistical validation. The discovered patterns correspond to earlier research, hence confirming the credibility of the results. Additional extensive testing is advised to improve statistical reliability and generalizability.

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