The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 2025

Volume 37, Pages 590-601

ICEAT 2025: International Conference on Engineering and Advanced Technology

Behavior of Recycled Aggregate Concrete Slab–Column Connection Strengthened by NSM GFRP Bars

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Abstract: The mixture which contains self-compacting concrete (SCC), and recycled aggregates (RA) has a high workability and good handling which is used in heavy reinforcement locations. The application of glass fiber-reinforced polymer (GFRP) bars as an environmental substitute in construction helps for decreasing natural resource exhaustion and waste. On the other hand, the bars provide high strength, low ductility, and resistance to corrosion material when compared to steel bars. The combination of SCCRA with a GFRP reinforced concrete members develop an innovative RC member with highly functional characteristics. The structural behavior of slabs cast from self-compacting reinforced concrete mixed with recycled aggregates (SSRCRA) and reinforced with glass fiber-reinforced polymer (GFRP) bars by near-surface mounted (NSM) techniques have been investigated in this study. The research highlights the effect of number and the diameter of GFRP bars on the performance of SSRCRA slabs. Five SCC-RA slabs with dimensions of (1200 ×1200 ×100) mm, reinforced with different diameters and configurations GFRP bars are cast and tested. All specimens are exposed to a static load until failure. The results illustrate that SSRC slabs strengthened with NSM GFRP bars display superior performance compared to conventional concrete slabs, with significant improvements in ductility and load capacity. Particularly, this research demonstrates that increasing the number of GFRP bars enhances the load capacity by 31% and improves the ductility by 63% compared with control slab. Also, increasing of diameter of GFRP bars from 6 to 10 mm resulted in a reduction of the failure area and rising of load capacity with controlled deflection response. Overall, strengthening the SCC-RA slabs with NSM-GFRP bars leads to enhance stiffness, ductility, and structural performance.

Keywords: Self-compacting concrete (SCC), Recycled aggregate (RA), NSM GFRP bars, Sustainable construction, Flexural strengthening

Introduction

As a flooring mechanism, reinforcing concrete (RC) slabs are frequently utilized in office buildings, warehouses, parking garages, and other buildings with multiple stories. In common, the direct support of flat slabs are columns, whether or not drop panels or column capitals are used. This creates a clear space that is both visually and practically appealing without the need for dropping beams. The most crucial component of the The structural system comprises the slab-column connection because of its vulnerability fragile and abrupt punching failure of shear (Guandalini, 2009). This type of failure can also occur when special installations place a lot of concentrated loads on the columns or when the columns are promoted on the slab. By selecting the appropriate slab thickness, column capital, and additional particular reinforcement for shear, typical design scenarios can avoid failures of this kind (Brikle, 2008). Consequently, existing structures must be strengthened due to inadequate punching shear capacity caused by a variety of factors, including alterations to the building's use, the addition of new installations, or design and construction errors (Oliveira, 2000). Numerous punching shear strengthening methods have been the subject of significant research in recent decades (Elbakry, 2015).

Nowadays, the construction Environmental concerns and the depletion of natural resources are putting increasing pressure on the sector to adopt sustainable practices. Using recycled aggregates (RA) from construction and demolition debris in the production of concrete is one technique. (Panda, 2013). However, RA may reduce concrete strength, necessitating additional reinforcement (Kou, 2012). The utilisation of recycled concrete aggregates (RCA) in reinforced concrete slabs has attracted increased attention as a sustainable alternative to natural aggregates. Several investigations have analyzed the shear performance and structural behavior of RCA-based slabs, demonstrating their potential viability with suitable mix design and reinforcement strategies. Moser et al. (2012) (Schubert, 2012) studied the shear strength of reinforced concrete (RC) slabs without shear reinforcement. They used a variety of aggregates including 100% recycled concrete. According to their results of four-point bending, the shear strength of recycled concrete aggregate (RCA) slabs closely matched with predictions from the theory of critical shear crack and Eurocode 2, with a mean ratio of experimental values around 1.00 ± 0.05, additional studies expanded on these results. For example, Reis et al. (2015) examined the impact of recycled coarse aggregates concrete on the behavior of punching for RC slabs, resulting minimal effects on punching strength but noted reductions in cracking load. Francesconi (2016) found that RCA and natural aggregate slabs had equivalent punching shear strengths, while Xiao et al. (2019) discovered that increasing RCA percentages reduced punching shear capabilities and ductility, although steel fibres enhanced performance. Altaee (2020), Silva (2020), Xiao (2015), Noridah, and Poongodi (2021) conducted additional research on the mechanical properties and structural behaviour of concrete with recycled aggregates, indicating that, while these materials can maintain adequate structural performance, careful mix design and reinforcement strategies are required to optimise mechanical properties while ensuring safety.

Near-surface mounted (NSM) GFRP bars, on the other hand, are an efficient reinforcing option due to their high tensile strength, corrosion resistance, and light weight (Al-Mahaidi, 2011). Several experimental investigations have looked into various approaches for recovering and reinforcing reinforced concrete (RC) slabs in order to restore or improve their structural performance. These options range from traditional methods utilising cementitious materials and steel plates to sophisticated uses of Fiber-Reinforced Polymers (FRPs) and hybrid systems, each providing a distinct balance of increased load capacity and structural ductility (Baggio, 2014).

Using the information presented, several experimental experiments were conducted to investigate techniques for repairing and reinforcing reinforced concrete (RC) slabs. Initial studies, such as the one by Thanoon et al. (2005), compared traditional repair procedures such cement grout and epoxy injection to new strengthening approaches. These investigations discovered that, while all evaluated ways significantly increased the slabs' ultimate load capacities, traditional methods tended to maintain the original slab's ductility. Other studies focused on specific failure modes, with Hazem et al. (n.d.) demonstrating that externally bonded steel plates with studs could increase punching shear capacity by up to 39% while decreasing central deflection, highlighting the effectiveness of targeted steel reinforcement for specific structural deficiencies. A large amount of research has focused on the use of FRP, particularly carbon (CFRP) and glass (GFRP) composites, as a key strengthening option. These materials are applied in different forms, such as externally attached (EB) sheets, strips, or NSM bars. Studies by Makhlouf (2024), Ali (2016), and Alharty (2023) repeatedly indicate that FRPs may significantly boost the load-bearing capability of slabs, with claimed strength increases ranging from 67% to over 100% when compared to control samples. FRPs are versatile enough to be employed in various configurations to obtain significant improvements in flexural behavior and initial stiffness.

However, using FRP requires a substantial trade-off and careful material selection. Numerous studies have demonstrated that the large increase in strength caused by the use of FRP typically leads to a loss in the slab's overall ductility. Comparative investigations, such as Alharty (2023), found that for a comparable area, CFRP sheets had a stronger impact on strengthening than laminates and were more cost-effective. Furthermore, Makhlouf's work indicated that NSM-CFRP bars provided the highest strength increase among several techniques. Also, Ali (Ali, 2016) noted that by carefully selecting the strengthening material's properties relative to the existing steel reinforcement, it is possible to increase stiffness while maintaining the slab's ductile failure mode.

To address the limitations of individual methods, such as debonding or reduced ductility, researchers are developing innovative and hybrid strengthening systems of RC slabs. Firas introduced a novel technique combining A mechanical anchoring technique for a jacket made of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) to prevent premature debonding, successfully increasing load capacity by 82%. Similarly, (Demir, 2019) showed that adding polypropylene fibers to GFRP-reinforced slabs improves ductility and energy dissipation. Other advanced approaches include using Textile-Reinforced Mortar (TRM), ferrocement layers with high-performance meshes, With the Externally Bonded Embedded Concrete Cover (EBECC) and the Externally Bonded Embedded in Concrete Cover (EBECC) method, all of which aim to provide superior adhesion, protection, and a more balanced structural performance.

This study explores the performance of SSRC slabs made with RA and strengthened with NSM GFRP bars. The research aims toward assess whether the combination of RA and GFRP reinforcement can achieve structural performance comparable to conventional concrete.

Experimental Work

Simply supported SSRC slabs with overall dimensions (1200 ×1200 ×100) mm (length× width ×thickness) are considered in the experimental tests of this study, as Figure 1. The experimental program consisted into two mains stages: in the first stage the optimum self-compacting concrete RA mixture was designed by preparing self-compacting concrete (SCC) incorporates varying proportions of recycled coarse aggregates (RCA) which in turn obtained crushed old concrete slabs and cubes. Experimental investigations were performed to determine the conformity of concrete mixtures to the adopted standards and codes. The fresh properties of these mixes were determined the slump-flow and V-funnel tests were employed, while the mechanical qualities were assessed by compressive strength and splitting tensile strength, and modulus of rupture tests. However, the second phase includes the Processes of casting, curing, and testing for five self-compacting reinforced concrete slabs utilising 50% recycled concrete aggregate (RCA) and 50% natural coarse aggregate. (NCA) in concrete mix. Each slab specimen was reinforced by steel bars and strengthened by NSM GFRP bars and exposed to a static load until failure.

Materials Properties

The materials utilised in this study included Type I Ordinary Portland Cement., compatible with Iraqi specification No. 5:2019, with a fineness of 320 m²/kg and a 28-day compressive strength of 49.3 MPa, natural coarse aggregate (NCA), with a maximum particle size of 14 mm, complied with Iraqi standards (I.Q.S No. 45/1984). However, the recycled coarse aggregate (RCA) used as a 50% spare of the natural coarse aggregate was sourced from crushed old concrete slabs and cubes and processed through washing and sieving to ensure quality with a maximum particle size of 5-14 mm. Limestone powder was added to enhance the cohesion and fluidity of self-compacting concrete (SCC) at up to 20% of the cement weight, following EFNARC Guidelines (2005) (EFNARC, 2005). MasterGlenium® 54 superplasticizer was also utilized to improve workability by reducing the water-to-cement ratio, as detailed in Table 1. Reinforcement was provided by steel bars of Ø 8 mm and Ø 10 mm diameters, compliant with ASTM A615M-09b, while GFRP bars, known for their high tensile strength and corrosion resistance, were employed as NSM strengthening bars at diameters of Ø 6 mm, Ø 8 mm, and Ø 10 mm. As the bonding agent for the GFRP bars and the surrounding concrete in the NSM strengthening method, Sikadur-31/41 CF Slow epoxy adhesive was used and mixed in a 2:1 ratio to ensure effective bonding performance. Finally, For mixing and curing, pure tap water was utilised, guaranteeing ideal hydration.

Concrete Mix

Three mixtures of trail mix, each including three cubes, were prepared, set, cured, and evaluated, as depicted in Table 1. Each cube is 150 mm x 150 mm × 150 mm. After 24 hours, the cubes were demolded and immersed within water. Table 1 presents the characteristics of the trail mix and the mean compressive strength. findings for each mix. The concert mix corresponded to a compressive strength of approximately 40.10 MPa to have been chosen to cast the RC slab specimens in this study.

Table 1. Proportions of mixtures and associated compressive strengths

Mix code	Cement	Water	W/C	SP	SP%	LP	NFA	NCA	RCA	Average compressive strength (MPa)
RCA-A 50%	396	174	0.44	6.1	1.54%	132	770	425	389	32.07
RCA-B 50%	403	174	0.43	6.2	1.54%	132	770	425	389	36.70
RCA-C 50%	430	174	0.40	6.62	1.54%	132	770	425	389	40.10

In this context, SP, LP, NFA, NCA, and RCA denote super-plasticizers, limestone powder, fine aggregate, coarse aggregate, and recycled coarse aggregate, respectively.

The Specimens of RC Slab

The research effort encompassed design, casting, curing, and testing of five self-compacting reinforced concrete (SSRC) simply supported square slabs at 50% percentages of recycled coarse aggregates (RCA) with dimensions of 1200 ×1200 mm and thickness of 100 mm as shown in Figure (1). A square column with cross sectional dimensions of 125×125 mm and 125 mm height were casted mantically with the slab at its centre. As illustrated in Figure (1) before, the slabs were reinforced at the bottom with steel bars of with 8 mm diameter spread along the section at 160 mm with flexure reinforcement ration (ρ) equal to (0.413). While the columns were longitudinally reinforced by four 10 mm diameter steel bars and transversely reinforced (stirrups) with 8 mm diameter steel bars spaced at 60 mm. The column was designed as dimensions and reinforcement to sustain the imposed load so than failure would be occurred at the slab rather than the column itself.

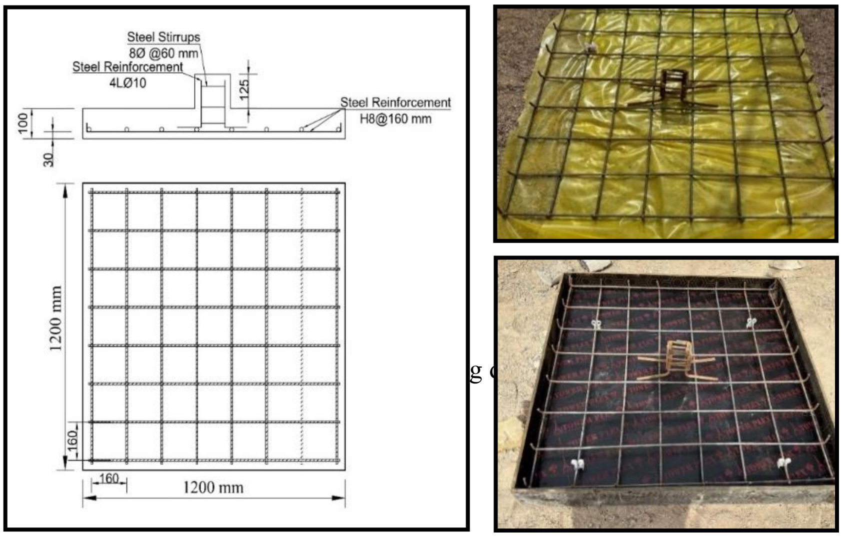


Figure 1. Specifications and reinforcing details of the evaluated slabs

Casting and Curing Column Specimens

Five cylinders, five cubes, three prisms, and five slab specimens were cast and cured in water for 28 days, illustrated in Figure 2. Cylinders, cubes, and prisms were fabricated from each mixture to ascertain the splitting tensile strength and compressive strength. and modulus of rupture, respectively corresponding to each mix batch. Tests results have shown that the corresponding average tensile, compressive strengths, and modulus of rupture were 3.37 MPa, 35.07 MPa, and 8.49 correspondingly.

Figure 2. Casting and curing the RC slab specimens, cubes, cylinders and prisms.

Application of NSM Process

This study used the NSM technique with GFRP bars to strengthen the RC slabs shown in Table 2 and Figure 3. The following steps describe the procedure adopted for strengthening the RC slabs using this technique in accordance with the standards proposed by ACI Code 440.2R-17 (ACI, 2017).

Table 2. Specification and dimensions of the near-surface mounted technique.

Slab designation	Type of bar	No. of bar	Diameter of bar (mm)	Bond length (mm)	Spacing (mm)	Groove size (mm)	Adhesive
S50C	control						
S50-2GØ6	GFRP	8	6	420	100	10×10	Epoxy
S50-2GØ8	GFRP	8	8	420	100	12×12	Epoxy
S50-2GØ10	GFRP	8	10	420	100	15×15	Epoxy
S50-3GØ8	GFRP	12	8	420	45	12×12	Epoxy

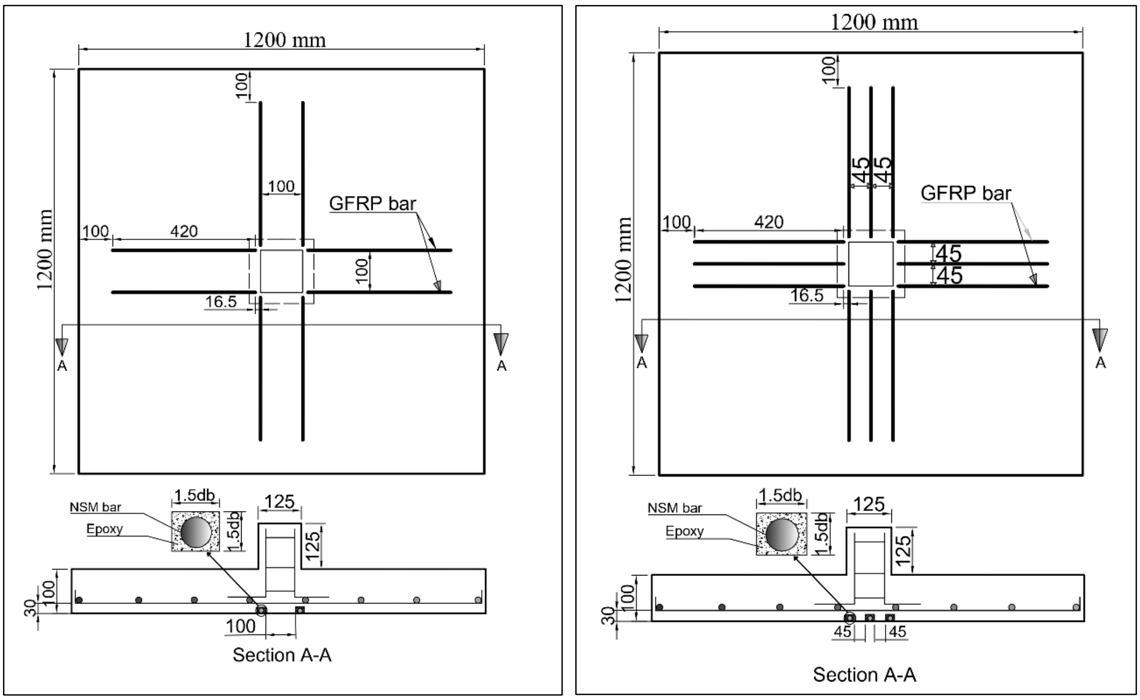


Figure 3. Strengthening scheme

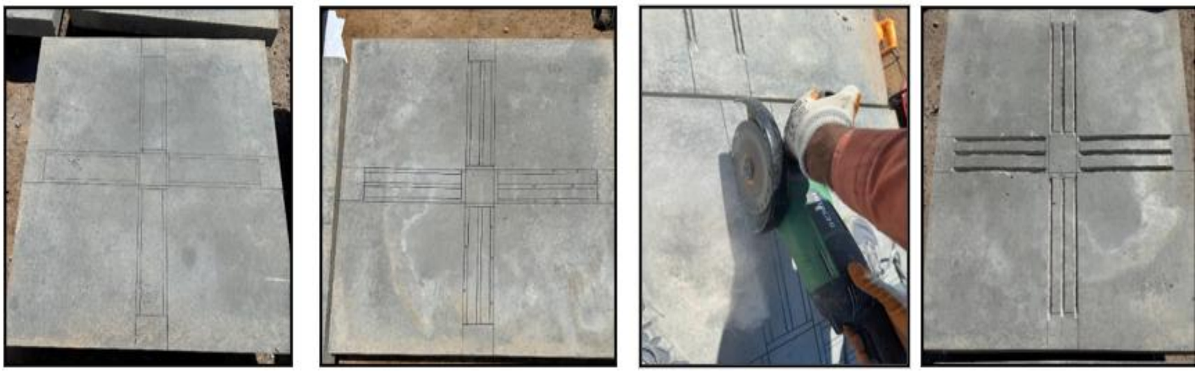
Preparation of the Specimen Surface

- The outlines of grooves on the concrete surface has been determined based on the strengthening configuration, as shown in (figure 4-a).
- The grooves have been cut, with a diamond blade, through the concrete overlay of slabs at the required locations and alignments with defined dimensions of (1.5db×1.5db) mm (width × depth) on both sides of the slabs (Figure 4-b) as suggested by ACI- code 440.2R-17 (ACI, 2017). Then, the grooves were cleaned well to ensure strong adhesion, as shown in Figure (4-c).

Placing of NSM GPRP

- Cutting GFRP bars according to the required dimensions as shown in Figure (4-d).
- Mixing the epoxy according to manufacturer technical data by slow speed an electric mixer. Afterward, Epoxy A and the hardener B contained used in a 2:1 ratio to achieve a homogeneous grey coleus, shown in the figure (4-e).
- Subsequently, the grooves were partly filled with epoxy paste, and GFRP bars were installed. Gentle pressure was used to ensure the glue thoroughly enveloped the bars. Figures (f, g, and h) illustrate that

the grooves were adequately filled and levelled, and the slabs were allowed to cure for two weeks to ensure the concrete and bars attained the requisite bonding strength.



a) Groove layouting b) Carving the grooves

c) Purging the grooves d) Cutting GFRP bars e) Mixing the epoxy f) Placing epoxy

g) Positioning GFRP bars h) Levelling out and filling the grooves i) Final Shapes for Specimens

Figure 4. Strengthening procedure of the RC slab specimens

Test Preparation and Instrumentations

The slabs specimens in this investigation were tested using a loading frame machine, which includes a hydraulic operator, load cell, steel girder, and steel frame for applying one-point load. The testing machine (see Figure 5-a), which has capacity of around 1000 kN, was available at the structural laboratory of Al-Qadisiyah University's Civil Engineering Department (Al-Naqeeb, The behavior of reinforced concrete columns exposure to eccentric loads at high temperature (Al-Naqeeb, 2021). Structural behavior of lightweight reinforced concrete columns subjected to eccentric loads at high temperature. All specimens were tested under one-point load using a rigid steel (I-section) frame up to failure. A steel frame was fabricated to simply support the slab specimens. To prevent the corners from lifting too much when being loaded, the specimens' corners were supported by seven steel pieces that served as a steel lever. To support the system, this was installed on the upper surface of the device testing base. As shown in Figure (5-b), four steel bars with a diameter of 25 mm were welded at the top steel frame to simulate simply support boundary condition for square specimens with an effective span of 1100 mm.

a) Test setup

b) Simple support depiction

Figure 4. Test setup used in the present study

Discussion of the Results

Effect of Number of GFRP Bars in Strengthening Slabs

Load Displacement Response

Figure 6 shows a comparison of the forces - displacement relationships of the control S50C and strengthened RC slabs with two (S50-2GØ8) and three (S50-3GØ8) NSM GFRP. The comparison reveals notable differences in terms of flexural behaviour as well as load-bearing capability. According to the illustration, the control specimen, S50C, exhibited a moderate increase in load with increasing deflection, reaching a maximum load of approximately 86 kN with a corresponded deflection of around 17.4 mm measured by LVDT. This indicates limited strength and ductility under flexural stress compared with the S50-2GØ8 slab, which demonstrated significantly improved performance, sustaining loads exceeding 98 kN with corresponded deflections greater than 23.8 mm. This indicates a more ductile behaviour and higher energy absorption of the S50-2GØ8 slab, suggesting that the using two NSM GFRP bar effectively enhanced the capacity to deformability of the strengthened slabs without experiencing brittle failure.

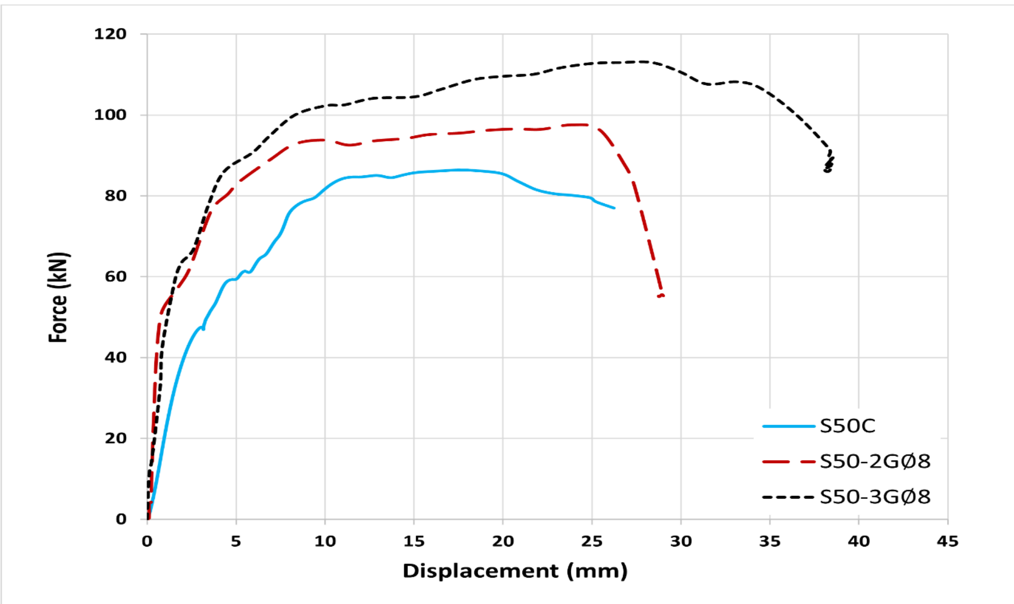


Figure 5. Effect of number of GFRP bars

In addition, Figure 6 shows that the S50-3GØ8 specimen gained the highest load capacity among the three specimens, with loads surpassing 113 kN and moderate deflections around 28.345 mm. This response indicates superior stiffness, ultimate strength, and balanced ductility compared to the control, both strengthened slabs (2GØ8 and 3GØ8) offered clear improvements in flexural performance specially S50-3GØ8 achieved both high strengths, making it the most structurally efficient configuration in this study. These findings underscore the efficacy of tailored NSM strengthening approaches in improving the mechanical behaviour of RC slabs under flexural loading, as shown in Figure 6.

Failure Modes

Figure 7 shows that increasing the number of GFRP bars causes significant decrease in the damaged area and failure cone of about 36 % compared with the control slab. This suggests that utilizing more GFRP bars can enhance the structural integrity of the slab and prevent catastrophic. While the decrease in failure area is modest, it highlights the potential benefits of optimizing bar quantity in design. These findings underscore the importance of considering both the number and configuration of reinforcement bars to improve overall performance in construction applications.

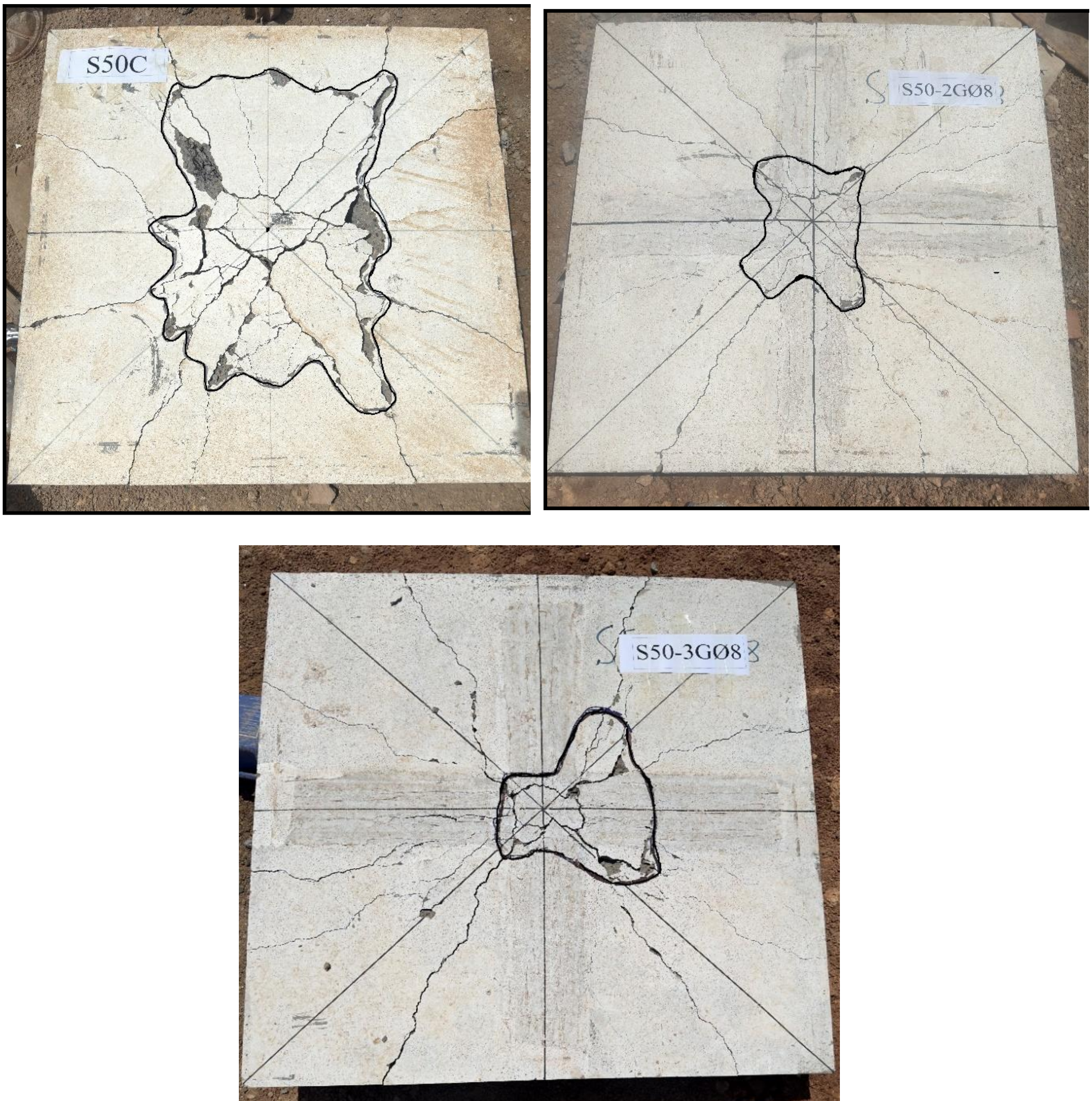


Figure 6. Failure modes of slabs strengthened by 2, and 3 GFRP bars using 8 mm bar diameter

Effect of Diameter of GFRP Bars in Strengthening Slabs

Load-Displacement Response

Table 3, and Figure 8 indicate that increasing the diameter of GFRP bars from 6 mm to 10 mm has a significant impact on the performance of SCCRA slabs with 50% recycled aggregate. For this work, the ultimate load capacity of the control slab specimen is 86 kN, this capacity increases to 95 kN with 6 mm bars, representing a 10% enhancement. When using 10 mm bars, the load capacity further rises to 110 kN, indicating a total increase of 15.79% and 27.9% compared to the 6 mm configuration and control specimen respectively (see Figure 8). This trend highlights that larger diameter bars provide greater resistance to applied loads, thereby improving the overall structural integrity of the slabs. However, increasing the bad diameter beyond specific value may cause a reverse effect due to interaction other parameters such as increasing the groove size resulting in less cover size.

In addition to increased load capacity, the diameter of GFRP bars also influences the deflection of SCCRA slabs under load. Figure 6, the maximum deflection for control specimen is 26 mm, while with 6 mm bars were provided, the maximum deflection increases to 31 mm. Further increasing the diameter to 10 mm could result in an average deflection of 32 mm, leading to a total increase of 3.2 % compared to the 6 mm bars, which means slight growing in deflection attitude. This response indicates that larger diameter bars enhance the stiffness of the slabs, making them more effective at maintaining structural performance under varying loading conditions, as shown in Figure 8.

Table 3. Experimental results of the control and strength of RC slabs with NSM GFRP bars

No.	Slab designation	First crack Load (Kn)	Increase in first crack load %)	Ultimate load (Kn)	Increase of ultimate Load %	Max deflection mm	Increase of Max deflection %
1	S50C	43.2	------	86	------	26	------
2	S50-2GØ6	49.2	13.9	95	10.46	31	19.23
3	S50-2GØ8	53.2	23.15	98	13.95	29	11.54
4	S50-2GØ10	66.1	53	110	27.9	32	23.08

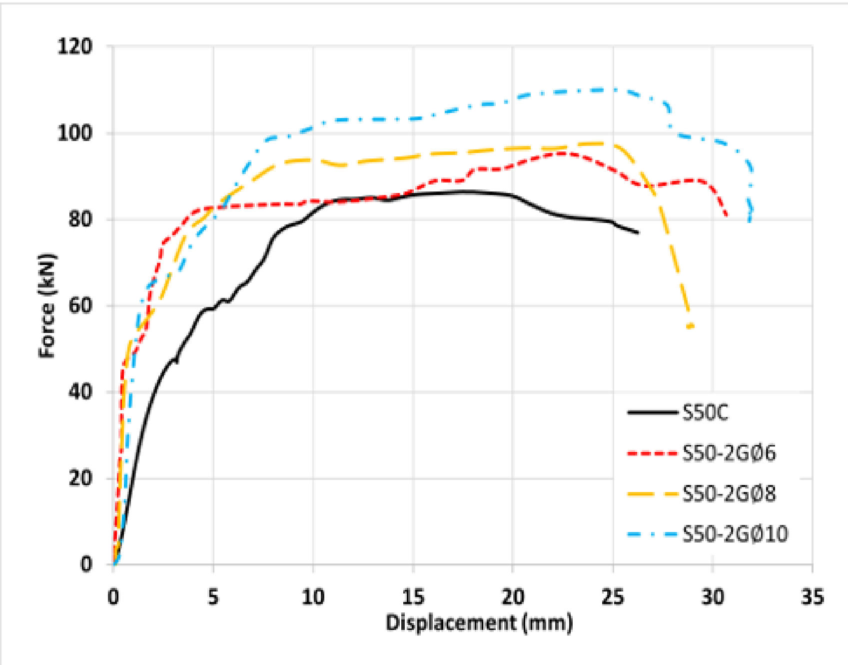


Figure 8. Load-displacement behaviour of SSRC slabs strengthened with NSM GFRP bars

Failure Modes

The failure modes shown in Figure (9) revealed that increasing the diameter of GFRP leads to decrease the failure cone and damage area. It can be seen from this figure that the failure area decreased by about 35%, 38% and 46% compared to the control slab by using 6 mm, 8 mm and 10 mm diameter of NSM GFRP bar respectively. This behaviour indicates that larger diameters enhance the failure and damage performance of GFRP bars which suggest that selecting an optimal diameter is crucial for improving the reliability and durability of RC slabs strengthened utilizing NSM GFRP reinforcement. Therefore, engineers should consider these findings when designing and selecting materials for strengthening RC members to ensure enhanced load-bearing capabilities.

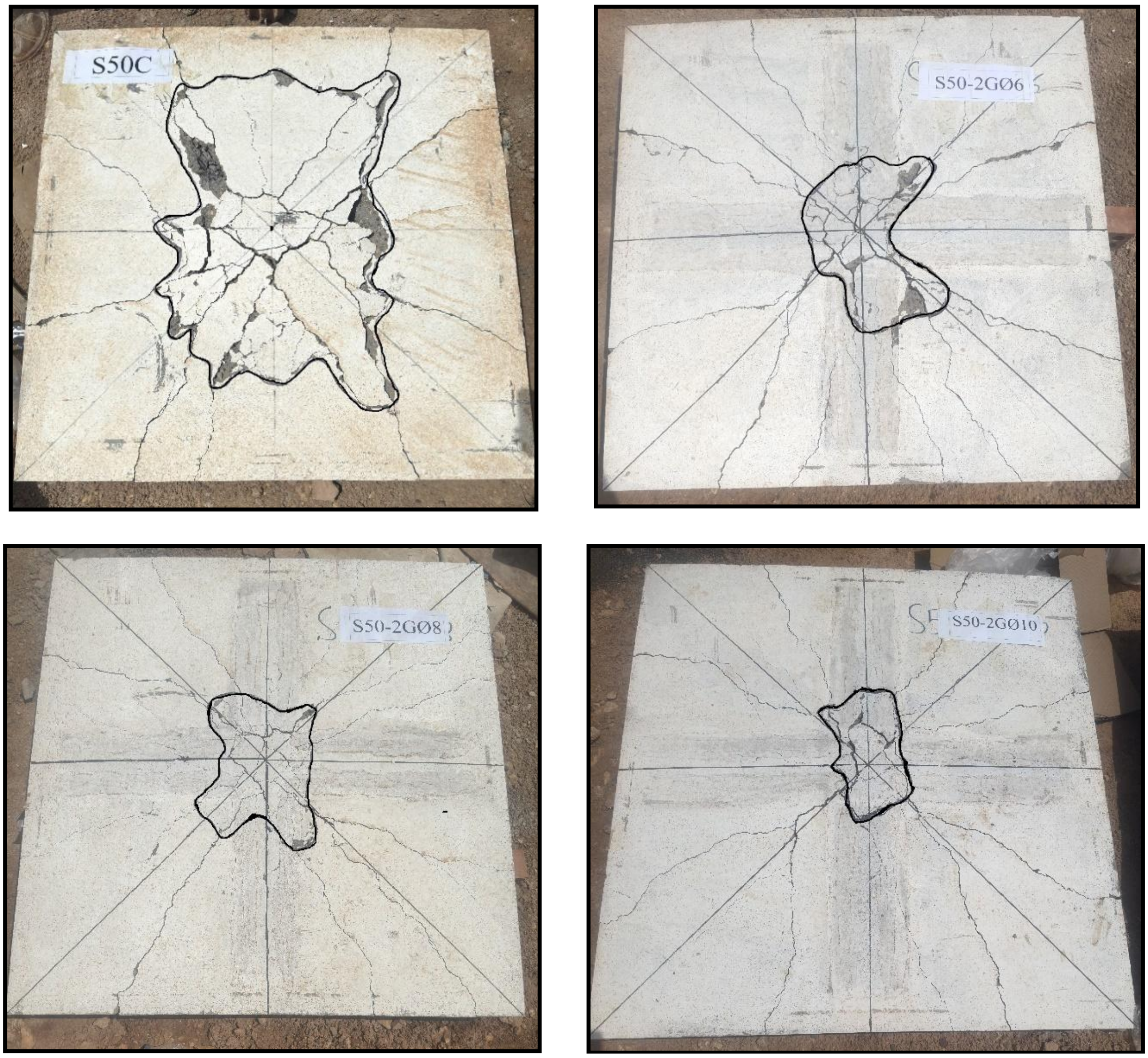


Figure 7. Failure modes of slabs strengthened by 2 GFRP bars with diameters 6mm, 8mm, and 10 mm

Conclusion

This research examines the impact of strengthening self-compacting reinforced concrete (SSRC) slabs made from recycled aggregates (RA) with near-surface mounted (NSM) glass fiber reinforced polymer (GFRP) bars. Five SSRC slabs were considered in the experimental tests, four of which were strengthened using NSM GFRP bars and one slab considered as a reference specimen. All RC slabs were loaded under one pint load up to failure and the findings from the experiment in terms of ultimate load, load-displacement relationships and failure modes are monitored, recorded and evaluated thoroughly. The following conclusions can be extracted from the experimental tests results:

1. Increasing the number of NSM GFRP bars improves the load capacity for the structure with balanced ductility.
2. Increasing the diameter of NSM GFRP bars improves the load capacity with slight rise in deflection which means enhanced stiffness, and overall performance for the structure.
3. Increasing the number and diameter of NSM GFRP lead to reduction in failure region which means superior structural integrity, and improved reliability for the structure.

Generally, the use of NSM GFRP bars to strengthen the RC members with recycled coarse aggregate significantly enhances the mechanical performance of SSRC slabs, improving both load-bearing capacity and ductility. The results emphasise the capability of combining the innovative strengthening techniques in RC members with sustainable construction materials while maintaining the response of conventional concrete.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

Funding

* Without funding

Acknowledgements

* This article was presented as a presentation at the International Conference on Engineering and Advanced Technology (ICEAT) held in Selangor, Malaysia on July 23-24, 2025.

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To cite this article:

Kadhum. K. R., & Al-Thairy, H. (2025). Behavior of recycled aggregate concrete slab–column connection strengthened by NSM GFRP bars. *The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 37,* 590-601.