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Flexural Performance of RC Slabs including Recycled Crumb Rubber (CR), Glass Powder (GP), and Steel Fibers (SFs)

Enas M. Mories* [1], Sherif A. El Beshlawy[1], Tarek S. Mustafa [2], and Ahmed A. Mahmoud[2]

[1] Construction and Building Engineering Department, Higher Institute of Engineering, October 6th City, Egypt.
[2]Department of Civil Engineering, Faculty of Engineering at Shoubra, Benha University, Cairo, Egypt.
[*] Corresponding Author.
E-mail: enasmedhat888@gmail.com; beshlawys@csi.edu.eg; tarek.mohamed@feng.bu.edu.eg; ahmed.ahmed@feng.bu.edu.eg

Abstract: The present paper investigates the flexural performance of reinforced concrete (RC) slabs incorporating waste crumb rubber (CR) and glass powder (GP). Seven concrete mixes were created with varying CR as a replacement for fine aggregate (0%, 10%, and 20% by volume), and GP as a cement substitute (0%, 10%, and 20% by weight). Steel fibers were added in order to enhance ductility and mitigate brittleness. Seven simply supported one-way RC slabs (2200 × 800 × 100 mm) were tested under two-line loads, using a mix designed for a strength of 40.3 MPa. The experimental results showed that substituting fine aggregates with 10% CR and cement with 10% or 20% GP leads to satisfactory slab performance. The 10% CR replacement emerged as optimal. Additionally, steel fibers significantly improved the performance, stiffness, and toughness of the slabs containing CR and GP. The lab analysis included cracking and ultimate loads, deflections, crack patterns, load-deflection relationships, stiffness, ductility, and toughness. At a 20% crumb rubber (CR) replacement, splitting and compressive strengths dropped by 16.2% and 12.2%, respectively, compared to normal concrete. Nonetheless, both 10% and 20% CR replacements maintained acceptable performance in reinforced concrete (RC) slabs, with 10% being the most effective. Similarly, glass powder (GP) substitution at 10% and 20% levels yielded satisfactory results, with 10% GP showing an 8.8% increase in failure loads. In contrast, 20% GP resulted in minor reductions in failure and crack loads by 14.7% and 5.9%.

Keywords: crumb rubber, glass powder, recycling materials, rubberized concrete, RC slabs.

1. INTRODUCTION

The utilization of recycled materials in concrete, such as crumb rubber (CR) and glass powder (GP), has gained significant attention in recent years [1,2] due to their potential to address environmental concerns and enhance the properties of concrete. CR, derived from waste tires, is a promising alternative to conventional fine aggregate (FA) in concrete. The annual production of concrete exceeds 3.8 billion cubic meters, making the conservation of natural aggregates a critical issue. CR has been explored as a replacement for FA, aiming to reduce the environmental impact of waste tires while also potentially improving concrete properties [3-5]. Rubberized concrete is known for its energy absorption capacity, though it often exhibits reduced load resistance [6]. However, studies have shown that CR can enhance concrete's toughness and ductility, making it a viable option for certain structural applications [7].

In addition to CR, the incorporation of glass powder (GP) into concrete has shown promise as a sustainable alternative to Portland cement. GP, produced from finely ground waste glass, contains a significant amount of amorphous silica, which exhibits pozzolanic behavior, thereby enhancing the durability and mechanical properties of concrete [8-9]. The use of GP not only addresses the disposal issues associated with non-biodegradable glass waste, but also contributes to the production of more environmentally friendly construction materials [10-11].

Research has demonstrated that combining CR with other materials, such as steel fibers (SFs) and recycled coarse aggregate (RCA), can further improve the mechanical properties and impact resistance of concrete. For instance, the addition of SFs to rubberized concrete has been shown to enhance flexural strength, abrasion resistance, and toughness, while also reducing weight loss [12-13]. Similarly, the inclusion of GP in concrete mixtures has been found to increase compressive and flexural strengths, particularly when combined with fibers [14-16]. Optimal performance has been observed with specific replacement ratios, such as 10% CR and 25% RCA or 10% GP and 1% steel fibers, where the balance between strength and ductility is achieved [17-19].

Furthermore, the integration of these recycled materials into reinforced concrete (RC) elements, such as beams and columns, has shown promising results. For example, RC beams containing GP exhibited improved flexural performance and resistance compared to control beams [20-21], while RC columns with GP showed enhanced load-bearing capacity and delayed cracking [22-23]. The combined use of CR and GP in concrete not only contributes to sustainable construction practices, but also offers potential improvements in the structural behavior and durability of RC elements [24].

Overall, the exploration of CR and GP as partial replacements for conventional concrete components holds significant promise for advancing sustainable construction practices. By addressing environmental concerns and enhancing the mechanical properties of concrete, these recycled materials can contribute to the development of more resilient and eco-friendly structures.

2.EXPERIMENTAL PROGRAM

2.1.Properties of Materials and Composition of the Concrete Mix

The materials used in the experimental study included Portland cement (CEM I 42.5 N), tap water, natural coarse and fine aggregates, admixtures, crumb rubber, glass powder, and steel fibers. Ordinary Portland cement (CEM I 42.5 N) with a 28-day compressive strength of 40.3 MPa, following ASTM C150 [25], were used for all concrete samples. Fine and coarse aggregates were also used, with their specific gravity and water absorption properties determined by ASTM standards C127 [26] and C128.[27]

Crumb rubber, sourced from recycled scrap and used tires, was another key material in the study. This resilient material, typically sized between 2 mm and 3 mm with a 30–40 mesh size, is shown in Figure 1. The physical properties of both natural aggregate and crumb rubber (CR) are presented in Table 1.

Finely-ground waste glass, reduced to a powder size of 600 microns, was used as glass powder (GP). This material is known to react with cement alkalis through a pozzolanic reaction, contributing to concrete strength and long-term durability [28]. The grinding process continued until 80% of glass powder passed through a 45 µm sieve. The chemical composition of GP, as determined by XRF analysis, is detailed in Table 2, while its physical properties are listed in Table 3.

Steel fiber (SF), a reinforcement material made from cold-drawn wire, was another essential component. These fibers, which are 50 mm long with a wavelength of 8 mm and a wave height of 2-2.5 mm, were used to improve the mechanical properties of concrete, following ASTM A820 [29], as illustrated in Figure 1.

Additionally, two types of steel reinforcement were used throughout the study: longitudinal reinforcements with diameters of 8 mm and 10 mm for the top and bottom sections. The mechanical properties of the steel reinforcement were evaluated in accordance with ASTM A370 [30], and the results are shown in Table 4.

FIG 1. Crumb rubber, steel fiber and glass powder

TABLE 1 The physical properties of CA, FA, and CR

Material type	Specific gravity	Water absorption%	Moisture content%
CA	2.50	1.91	1.87
FA	2.58	0.81	1.5
CR	1.14 ± 0.02	NA	NA

TABLE 2 Chemical Composition of GP and Cement (%)

Chemical Composition (%)	SIO_2	AL_2O_3	Cao	Fe_2O_3	MgO	K_2O	Na_2O	SO_3	TiO_2	LOI
GP	71.08	2.92	11.01	0.95	1.29	0.87	11.41	0.09	0.06	0.75
Cement	20.13	4.99	63.13	3.20	2.54	0.87	0.21	3.46	1.05	1.43

TABLE 3 Physical properties of GP

Density (kg/m^3)	2577
Specific weight	2.58
Percentage passing through sieve (fineness)	80 (45 μm)

TABLE 4 The properties of the used reinforcement bars

Φ (mm)	A_{act} (mm^2)	f_y (MPa)	$\varepsilon_{y\,(-)}$	f_u (MPa)	$\varepsilon_{u\,(-)}$	Elongation%	E_s (GPa)
8	**53.3**	**421.76**	**0.00241**	**585.69**	**0.09244**	**9.24**	**200**
10	**77.8**	**491.22**	**0.00360**	**640.44**	**0.08364**	**8.36**	**200**

Φ is the bar's diameter in mm.

A_{act} is the actual area of the steel bar;

f_y is the yield strength of the used steel bars (proofing strength at 0.02 strain);

ε_y is the strain at the yield strength of the used steel bars;

f_u is the ultimate strength of the used steel bars;

ε_u is the strain at the ultimate strength of the used steel bars, and

E_s is the Young's modulus of the used steel bars.

TABLE 5 Mixing proportions of concrete mixes /m^3

Mix no	Crumb Rubber		Glass Powder		Steel Fiber		Cement content (kg/m^3)	FA (kg/m^3)
	CR %	CR (kg/m^3)	GP %	GP (kg/m^3)	SF %	SF (kg/m^3)		
MNC	---	---	---	---	---	---	350	720
MCR1	10	32	---	---	---	---	350	648
MCR2	20	64	---	---	---	---	350	576
MCR3	10	32	---	---	1.0	78	350	648
MGP1	---	---	10	35	---	---	350	720
MGP2	---	---	20	70	---	---	315	720
MGP3	---	---	10	35	1.0	78	280	720

Where:

Coarse aggregate (CA) content of 1200 kg/m^3 concrete;

The water content of 175 liter/m^3 concrete; and

Supper Plastizer content of 3.5 kg/m^3 concrete.

TABLE 6 Specifications of the tested RC slab specimens

Slabs No.	Mix No.	Slabs Length (mm)	Slabs Width (mm)	Slabs thickness (mm)	CR %	GP %	SF %	Bottom reinforcement
								In the short direction
SNC	MNC	2200	800	100	---	---	---	Φ 10 mm @ 190 mm
SCR1	MCR1	2200	800	100	10	---	---	Φ 10 mm @ 190 mm
SCR2	MCR2	2200	800	100	20	---	---	Φ 10 mm @ 190 mm
SCR3	MCR3	2200	800	100	10	---	1	Φ 10 mm @ 190 mm
SGP1	MGP1	2200	800	100	---	10	---	Φ 10 mm @ 190 mm
SGP2	MGP2	2200	800	100	---	20	---	Φ 10 mm @ 190 mm
SGP3	MGP3	2200	800	100	---	10	1	Φ 10 mm @ 190 mm

2.2Design of concrete mixes

Seven concrete slabs were prepared in accordance with ACI 211.1 [31], incorporating crumb rubber (CR) as a partial replacement for fine aggregates at 0%, 10%, and 20% by weight. Additionally, glass powder (GP) was used as a partial substitute for cement at 0%, 10%, and 20% by weight. To further enhance the concrete properties, 1% steel fibers (SFs) were added to the optimal CR and GP mix ratios. The detailed mixing proportions are presented in Table 5.

2.3Specifications of the Tested RC Slabs

Seven reinforced concrete (RC) slabs were designed and subjected to testing. Each slab measured 2200 × 800 × 100 mm. The RC slabs were reinforced with main bottom bars of Φ 10 mm, spaced 190 mm apart in the short direction, and secondary bottom bars of Φ 8 mm, spaced 195 mm apart in the long direction. All slabs had a concrete cover of 25 mm, as illustrated in Figure 2.

The control slab, designated as “NC,” consisted of standard concrete without crumb rubber (CR), glass powder (GP), and steel fibers (SFs). CR was incorporated into the RC slabs at different percentages for slabs SCR1 and SCR2. Similarly, GP was added to the RC slabs at various percentages for specimens SGP1 and SGP2. SFs were introduced into the rubberized concrete with the optimal CR percentage (10% CR) at a volume fraction of 1%, as shown in slab SCR3. SFs were also added to the concrete with the optimal GP percentage (10% GP) at a 1% volume fraction, as depicted in slab SGP3. The specifications of the tested RC slab specimens are detailed in Table 6.

For each concrete mix, a total of six cubes measuring 150 x 150 x 150 mm and three cylinders with a diameter of 150 mm and a height of 300 mm were cast. The specimens were tested on the designated testing day, with three cubes tested at 7 days and the remaining three at 28 days. The cubes were employed to determine the compressive strength of the concrete according to ASTM C39 [32]. The stress-strain curves for concrete in compression were plotted using ASTM C1232 [33], which also facilitated the measurement of strain at maximum compressive strength and the calculation of the concrete's elastic modulus. Additionally, the splitting tensile strength was evaluated using the concrete cylinders in accordance with ASTM C496 [34].

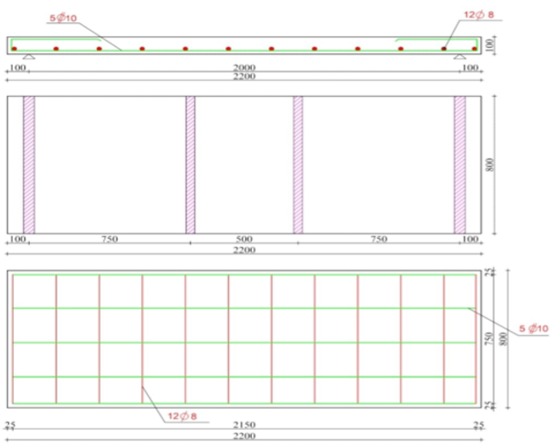


FIG 2. Details and Dimensions of Reinforced Concrete Slabs

2.4Test Slab Setup

The slabs were thoroughly cleaned and painted prior to testing to ensure that cracks were clearly visible during and after the experiment. Each RC slab was subjected to loading until failure. The slabs were tested as simple spans supported at their two ends, with two solid bars of 50 mm diameter placed underneath and subjected to two-line loads using a 200 kN capacity load cell. The effective span for the test was 2000 mm. Crack patterns were meticulously recorded. Mid-span deflection was measured with an LVDT (Linear Variable Differential Transducer) positioned at the midpoint of each slab. Both the applied load and the corresponding deflection were documented for each slab. The test setup is depicted in Figures 3 through 8.

FIG 3. Setup for slab testing

FIG 4. Configuration for concrete compressive strength testing

FIG 5. Configuration for testing concrete cylindrical compressive strength

FIG 6. Setup for testing splitting tensile strength of cylinders

FIG 7. Configuration for testing steel bars

FIG 8. Detailed depiction of the tested slab specimens

3.EXPERIMENTAL RESULTS OF TESTED MATERIALS

3.1Compressive strength test

The compressive strength test results for concrete cubes, evaluated at 7 and 28 days, are detailed in Table 7, with the mechanical properties of the concrete mixes shown in Table 8. The data reveal a reduction in compressive strength as the percentage of crumb rubber (CR) increased. For example, the compressive strength of the control concrete mix (MNC) without CR, glass powder (GP), and steel fiber (SF) was recorded at 40.3 MPa after 28 days. Increasing the CR content from 10% (MCR1) to 20% (MCR2) resulted in a decrease in compressive strength for the cubes and cylinders, ranging from 7.6% to 12.2% and 6.9% to 27.6%, respectively, when compared to the normal concrete (MNC). Moreover, the inclusion of CR and SFs improved the cubic compressive strength by 5.9% and the cylindrical compressive strength by 11.5% with 10% CR and SF volume fractions (1%), relative to the normal concrete (MNC). These and 5,3results align with findings from previous studies [1, 6].3

The substitution of cement with small proportions of glass powder had a minimal impact on the compressive strength of the concrete mixes at both 7 and 28 days. When 10% glass powder (GP) was used as a partial cement replacement (MGP1), the concrete cubes demonstrated a 5.3% increase in compressive strength at 7 days and a 3.3% increase at 28 days. Likewise, the compressive strength showed a 4.7% increase after 28 days compared to the control mix (MNC), which contained no recycled materials. In the case of mix (MGP2), which used 20% GP as a replacement for cement, there was a slight reduction in compressive strength, with decreases of 6.6% and 7.6% for cubes and cylinders, respectively, after 28 days compared to the control mix (MNC). Additionally, the inclusion of both GP and steel fibers (SF) resulted in increased compressive strength for both cubes and cylinders after 7 and 28 days. Specifically, mix (MGP3), which included 10% GP and 1% SF, showed an improvement in compressive strength of 8.4% for cubes and 13.8% for cylinders compared to the control mix (MNC). These results are consistent with findings from prior studies [13, 37- 40].

The failure modes of the concrete specimens are shown in Figure 9. Figure 10 illustrates the distribution of compressive stress-strain for concrete, varying with different levels of crumb rubber (CR) and glass powder (GP) content. Figure 11 presents the results of the cubic compressive strength tests for the concrete mixes at both 7 and 28 days.

TABLE 7 Concrete cubes properties

Mix No.	Cubes at 7 days					Cubes at 28 days				
	f_{cu} (N/mm^2)					f_{cu} (N/mm^2)				
	Cube 1	Cube 2	Cube 3	Average	Average /Average MNC%	Cube 1	Cube 2	Cube 3	Average	Average /Average MNA%

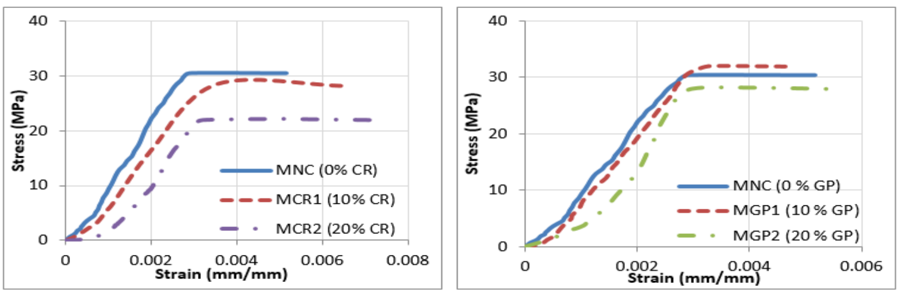
MNC	31.0	32.7	30.9	31.5	100.0%	39.1	40.8	41.1	40.3	100.0%
MCR1	29.4	28.1	28.6	28.7	91.0%	37.6	37.4	36.8	37.3	92.4%
MCR2	26.4	27.2	26.6	26.7	84.7%	34.6	36.2	35.4	35.4	87.8%
MCR3	33.2	31.8	31.4	32.1	101.9%	42.8	41.8	43.5	42.7	105.9%
MGP1	32.2	33.4	34.1	33.2	105.3%	41.8	40.9	42.3	41.7	103.3%
MGP2	30.2	30.1	29.7	30.0	95.1%	37.6	37.3	38.1	37.7	93.4%
MGP3	34.7	34.6	35.4	34.9	110.7%	42.5	43.8	44.8	43.7	108.4%

TABLE 8 The results of mechanical properties of the concrete mixes

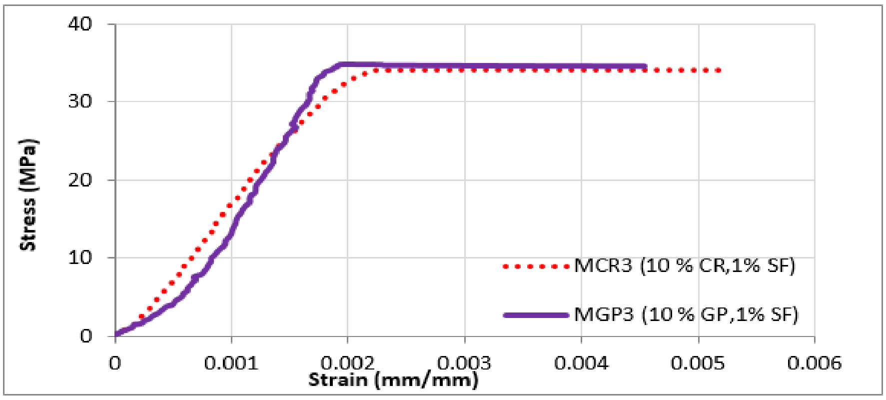
Mix No.	f_{cu} (MPa)		Axial Load P_c (kN)	Average of cylindrical compressive strength, f_c\`(MPa)	Splitting Load P_t (kN)	Tensile splitting strength, f_t (MPa)	Strain at maximum compressive strength, ε_0 (-)
	Average of 3 cubes at 7 days	Average of 3 cubes at 28 days					
MNC	31.54	40.33	541.5	30.64	154.3	2.183	0.00289
MCR1	28.70	37.27	504.2	28.53	145.7	2.061	0.00353
MCR2	26.73	35.40	392.3	22.20	132.3	1.872	0.00317
MCR3	31.90	41.87	589.2	33.34	202.7	2.868	0.00353
MGP1	33.21	41.67	32.07	104.7	2.31	106.0	0.00333
MGP2	30.00	37.67	28.32	92.4	2.13	97.7	0.00331
MGP3	34.90	43.70	34.87	113.8	2.84	130.3	0.00192

$f`c = P_c *1000/ (3.14*150*150)$; and
$f_t= 2*P_t*1000/ (3.14*300*150)$.

FIG 9. Compressive failure modes for concrete specimens

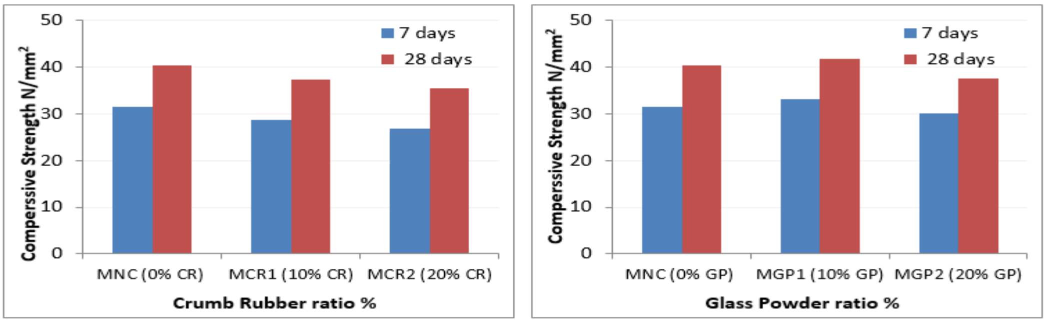


(a) Effect of CR % **(b) Effect of GP %**



(a) Effect of 1 % SF

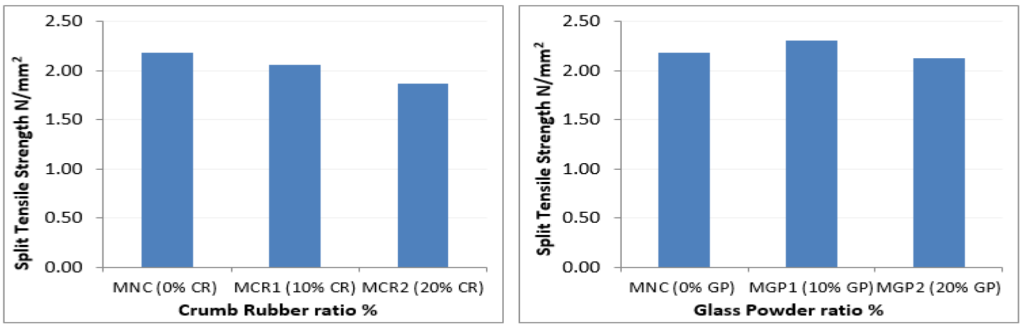
FIG 10. The compressive stress-strain relationship for the concrete with varying levels of crumb rubber (CR) and glass powder (GP)



Effect of CR % **Effect of GP %**

FIG 11. The results of the cubic compressive strength tests for the concrete mixes at both 7 and 28 days

FIG 12. Splitting failure modes for the concrete specimens



(a) Effect of CR content **(b) Effect of GP content**

FIG 13. Splitting tensile strength results for the concrete mixes

3.2Tensile Splitting Test

Table 8 presents the splitting tensile strength of various concrete mixes after 28 days. At this time, normal concrete achieves a splitting tensile strength of 2.183 MPa. However, as the crumb rubber (CR) content increases, there is a noticeable reduction in tensile strength, ranging from a 5.6% decrease with 10% CR (MCR1) to a 14.3% decrease with 20% CR (MCR2) compared to the normal concrete mix without rubber (MNC). On the other hand, the inclusion of both CR and steel fibers (SFs) significantly enhances the tensile strength. Specifically, the mix containing 10% CR and 1% SF (MCR3) shows a 43.2% improvement in tensile strength over MNC, indicating the positive influence of SFs. These results are consistent with previous research findings, as noted in references [1, 35, 36, 41, and 42].
Similarly, the effect of replacing cement with glass powder (GP) follows a trend comparable to the compressive strength results. When 10% GP is used as a cement replacement in mix MGP1, the splitting tensile strength increases by 6.0% compared to MNC, highlighting the beneficial impact of GP as a partial cement substitute. However, in mix MGP2, which contains 20% GP, there is a 2.3% reduction in tensile strength relative to MNC, indicating diminishing returns with higher GP content. Furthermore, the combination of GP and SFs leads to a notable enhancement in tensile strength; mix MGP3, with 10% GP and 1% SF, achieves a 30.3% increase in tensile strength over MNC. This improvement is largely attributed to the steel fibers' confining effect within the concrete mix. The experimental results align closely with findings from previous studies, as cited in references [43-46]. Figure 12 displays the failure patterns of concrete mixes subjected to splitting tensile tests. Similarly, Figure 13 illustrates the impact of the studied factors on the splitting tensile strength of the concrete mixes after 28 days.

3.3Testing of Steel Reinforcement

Steel reinforcement bars with diameters of 8mm and 10mm were evaluated using a testing machine with a capacity of 1500 kN, as depicted in Figure 7. The stress strain curves corresponding to these steel bars are presented in Figure 14. The mechanical properties of the steel used in the study are detailed in Table 4.

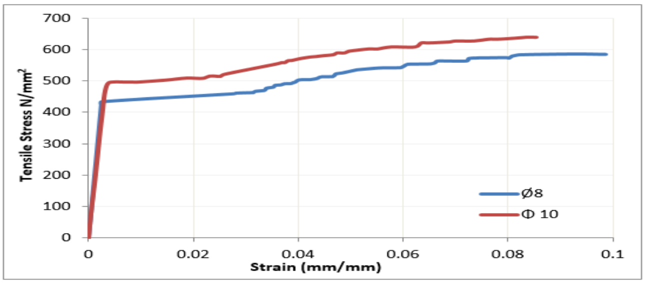


FIG 14. The stress-strain relationships for the reinforcement steel bars

4.EXPERIMENTAL RESULTS FOR RC SLABS

4.1 Crack patterns, crack load, and failure load

The crack patterns observed in all the tested RC slabs are depicted in Figure 15. It was observed that an increase in crumb rubber (CR) content led to an earlier appearance of the first crack. Cracks formed on the tension side of the slabs, running parallel to the loading and supporting lines, as shown in Figure 15. In the control slab (SNC), the first crack was recorded at a load of 21.3 kN. For the rubberized RC slabs, increasing the CR content from 10% in slab SCR1 to 20% in slab SCR2 resulted in a reduction in the first crack load by 6.1% and 15.5%, respectively. In slab SCR3, which included a 10% CR replacement and 1% steel fibers, the first crack occurred at a load that was 35.7% higher than the control slab (SNC).
In the RC slabs incorporating 10% and 20% GP, the first cracks were observed at loads of 23.34 kN and 20.08 kN for slabs SGP1 and SGP2, respectively. These initial crack loads represented 50%, 50.3%, and 55.2% of the total failure loads for slabs SNC, SGP1, and SGP2, as detailed in Table 9. Steel fibers were utilized to delay the formation of cracks in the RC slabs. For slab SGP3, which contained 10% GP replacement and 1% steel fibers, the first crack appeared at a load of 26.34 kN, indicating that the first crack load corresponded to 44.65% of the slab's failure load.

(a) Slab SNC (control slab)

(b) Slab SCR1 (10% CR)

(c) Slab SCR2 (20% CR)

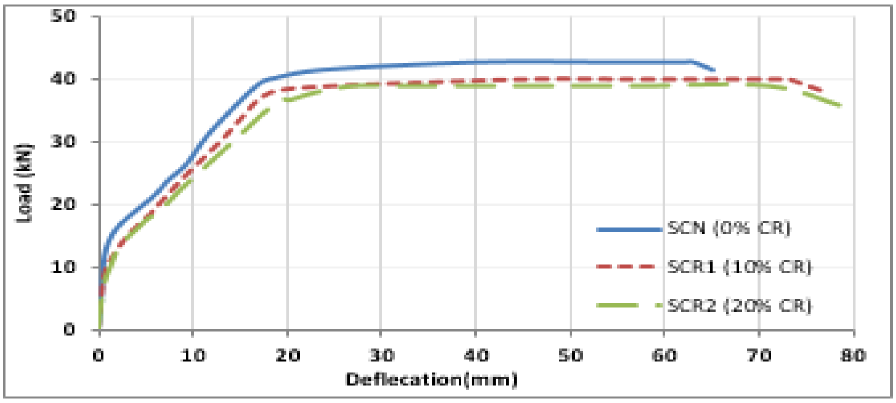
(d) Slab SCR3 (10% CR, 1 % SF)

(e) Slab SGP1 (10% GP)

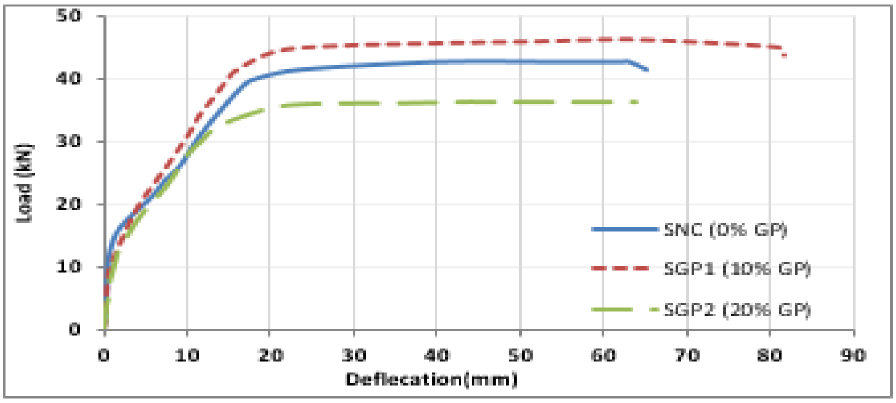
(f) Slab SGP2 (20% GP)

(g) Slab SGP3 (10% GP, 1 % SF)

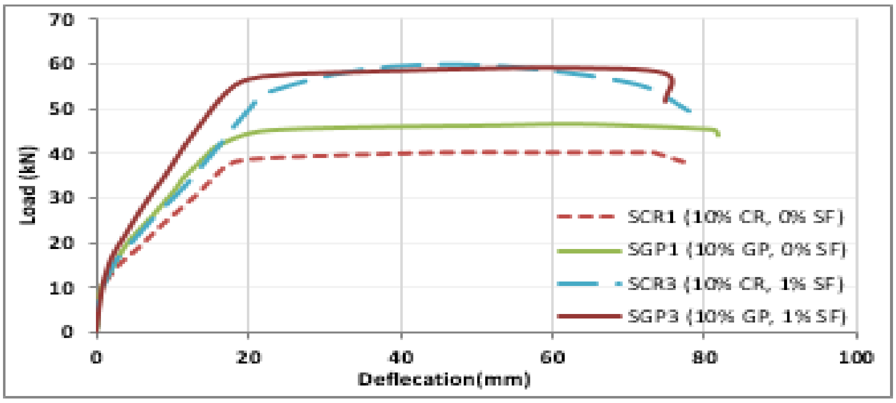
FIG 15. Crack patterns for all tested RC slabs



(a) Effect of CR content



(b) Effect of GP content



(c) Effect of 1% SF

FIG 16. Load deflection relationships for the tested RC slabs

4.2 Load-deflection relationships

Figure 16 illustrates the load-deflection behavior of the tested RC slabs. Figure 16.a presents the experimental load-deflection curves for the control slab (SNC), as well as rubberized RC slabs (SRC1 and SRC2). All the curves display a nearly linear trend in the ascending phase up to about 25% of the ultimate load. Beyond this point, as the load increases, the curves begin to exhibit bending due to the formation of internal micro-cracks. This figure clearly shows that as the crumb rubber (CR) content increases, the ultimate load capacity of the slabs decreases, while the deflection at failure load increases in comparison to the control slab (SNC), consistent with previous research findings [35 and 47]. As the load increases, so does the deflection, forming a curve until failure load is reached. Specifically, increasing the CR content from 10% to 20% led to a reduction in failure load by 5.9% and 8.8%, while the deflection at failure load increased by 18.2% and 21.5% for slabs S2 and S3, respectively, as summarized in Table 9.

Figure 16.b illustrates the load-deflection responses for RC slabs SNC, SGP1, and SGP2. The curves show a nearly linear

behavior in the ascending portion, up to approximately 20% of the failure load. This figure reveals that slab SGP1 exhibited a notably enhanced performance, both in terms of failure load and deflection at different load stages, compared to slabs SNC and SGP2. Specifically, SGP1 showed a 9% increase in failure load, while SGP2 experienced a 15% decrease in failure load. The deflection at the failure load for slab SGP1 was reduced by 2.0% compared to the control slab SNC. In contrast, slab SGP2 demonstrated a reduction in both failure load and deflection at failure load by 15% and 3.0%, respectively, when compared to the control slab SNC. These findings suggest that replacing 10% of cement with glass powder (GP) by weight significantly enhanced the failure load and deflection characteristics, as also highlighted in studies [20 and 43].

Figure 16.c illustrates the impact of incorporating crumb rubber (CR), glass powder (GP), and steel fibers (SF) on the load-deflection curves for slabs SCR1, SGP1, SCR3, and SGP3. The data reveal that increasing the SF ratios enhances the failure load capacity. The curves for these slabs exhibit a similar trend in the initial portion of the ascending branch, up to approximately 25% of the failure load. Notably, as the volume fraction of SF increases, the deflection at the failure load (Δf) decreases. Specifically, for specimens SCR3 with a 1% SF content, the failure load increased by 48.9% compared to slab SCR1 incorporating 10% CR, while the deflection at failure reduced by 27.6%. Additionally, slab SGP3, incorporating 10% GP and 1% SF, demonstrated a 38.0% increase in failure load and a 5.0% decrease in deflection at failure compared to the control slab SNC. These results underscore the beneficial effects of steel fibers on improving both the failure load and deflection characteristics of the concrete slabs.

4.3Displacement ductility (DD)

Displacement ductility (DD), which is the ratio of deflection at failure (Δf) to deflection at yield (Δy), is detailed in Table 9 for all tested RC slabs. Slab SCR1, incorporating 10% crumb rubber (CR), exhibited a 12.7% increase in DD. In contrast, when the CR content was elevated to 20% in slab SCR2, DD decreased by 5.8%. Adding 1% steel fiber (SF) to the CR mixture in slab SCR3 resulted in a substantial reduction in DD by 34.3%. On the other hand, slab SGP1, which included 10% glass powder (GP), demonstrated a 17% increase in DD compared to the control slab SNC. Increasing the GP content to 20% in slab SGP2 led to a 32% enhancement in DD over SNC. The incorporation of 1% SF in slab SGP3 produced a slight 3% reduction in DD relative to SNC. These observations align with findings reported in [48].

4.4 Initial stiffness (K)

Initial stiffness (K) is defined as the ratio of the yield load (Py) to the displacement observed at that load level (Δy). The experimental results for all tested RC slabs are summarized in Table 9. It was observed that initial stiffness decreased progressively with increasing amounts of crumb rubber (CR) used as a replacement for fine aggregate (FA) by volume. Specifically, incorporating 10% and 20% CR into slabs SCR1 and SCR2 led to reductions in stiffness of 2% and 11.5%, respectively. In contrast, the addition of steel fiber (SF) to the CR mixes in slab SCR3 resulted in a notable increase in stiffness by 11.8%. According to Table 9, slab SGP1, which includes a 10% glass powder (GP) replacement, demonstrated a significant increase in stiffness of 22%. Further increasing the GP replacement to 20% in slab SGP2 yielded a 10% improvement in stiffness, aligning with previous research findings [44]. Additionally, the combination of glass powder and steel fibers in RC slabs further enhanced stiffness. For slab SGP3, which incorporates 10% GP and 1% SF, the stiffness increased by 41% compared to the control slab SNC.

4.5 Toughness (I)

Energy absorption, or toughness, is quantified as the area under the load-deflection curve, as detailed in Table 9. The toughness of the slabs consistently improved with increased crumb rubber (CR) content, greater slab thickness, and higher reinforcement ratios. Specifically, enhancing the CR content from 10% in slab SRC1 to 20% in slab SRC2 led to increases in toughness of 12.6% and 12.1%, respectively. Slab SRC3, which incorporated 1% steel fiber (SF) along with 10% CR as a replacement for fine aggregate (FA), exhibited a substantial toughness increase of 58%. Substituting 10% of the cement with glass powder (GP) in slab SGP1 resulted in a significant 39% rise in toughness compared to the control slab SNA. Conversely, increasing the GP replacement to 20% in slab SGP2 caused a 15% decrease in toughness relative to the control slab, aligning with findings from previous research [44]. Additionally, RC slab SGP3, which included 1% steel fibers, demonstrated a notable toughness enhancement of 59% compared to the control slab SNC.

TABLE 9 Experimental results of the tested RC slabs

Slab No	Experimental Results								Relative Experimental Results to the Control Slab (SNC)							
	Pcr kN	Py kN	Dy mm	Pf kN	Df mm	K kN/mm	I kN.m m	DD	$\frac{P_{cr}}{P_{cr-S1}}$	$\frac{P_y}{P_{y-S1}}$	$\frac{D_y}{D_{y-S1}}$	$\frac{P_f}{P_{fS1}}$	$\frac{D_f}{D_{f-S1}}$	$\frac{K}{K_{S1}}$	$\frac{I}{I_{S1}}$	$\frac{DD}{DD_{S1}}$
SNC	21.34	40.16	18.83	42.67	65.17	2.133	2464.69	3.461	1	1	1	1	1	1	1	1
SCR1	20.08	37.99	18.17	40.16	70.88	2.091	2775.42	3.901	0.94	0.95	0.96	0.94	1.09	0.98	1.13	1.13
SCR2	18.83	36.68	19.44	38.91	71.16	1.887	2762.69	3.660	0.88	0.91	1.03	0.91	1.09	0.88	1.12	1.06
SCR3	27.61	53.60	22.48	59.79	51.30	2.384	3893.17	2.282	1.29	1.33	1.19	1.40	0.79	1.12	1.58	0.66
SGP1	23.34	41.15	15.85	46.44	64.07	2.597	3416.20	4.044	1.09	1.02	0.84	1.09	0.98	1.22	1.39	1.17
SGP2	20.08	32.63	13.95	36.40	63.51	2.340	2091.45	4.554	0.94	0.81	0.74	0.85	0.97	1.10	0.85	1.32
SGP3	26.34	55.22	18.40	58.99	61.83	3.001	3906.92	3.360	1.23	1.38	0.98	1.38	0.95	1.41	1.59	0.97

5. CONCLUSIONS

This study involved an experimental investigation of seven reinforced concrete slabs to assess their material & structural behavior, focusing on the effects of replacing fine aggregate (FA) with crumb rubber (CR) by volume, substituting cement with glass powder (GP) by weight, and incorporating steel fibers (SFs). The research also investigated the concrete specimens' properties. Based on the range of factors analyzed and the experimental results obtained, the following conclusions have been reached:

1. An increase in CR content led to a consistent decline in the compressive and splitting tensile strengths of the concrete mixtures. When the CR content reached 10%, the concrete's strength, stiffness, and ductility were only marginally affected.
2. Increasing the CR content from 10% to 20% in concrete mixes resulted in a reduction in compressive strength by 7.6% and 12.2%, and a decrease in splitting tensile strength by 5.6% and 14.3% after 28 days. Likewise, the failure load of RC slabs dropped by 5.9% and 8.8%.
3. Although the strengths were reduced, the inclusion of CR content enhanced the toughness and deflection at failure of the slabs. Toughness consistently increased with greater CR content, slab thickness, and reinforcement ratios. Incorporating 1% steel fibers into rubberized RC slabs with 10% CR replacement increased slab strength by 40.1%.
4. Substituting 10% of the cement with glass powder led to a 5.3% and 3.3% increase in compressive strength at 7 and 28 days, respectively. This replacement also boosted compressive strength by 5.6% and tensile strength by 4.7% at 28 days.
5. The best outcomes were achieved with a 10% glass powder replacement, which enhanced both compressive and tensile strengths. However, increasing the substitution to 20% resulted in a significant reduction in strength.
6. Slabs with a 10% glass powder substitution experienced an 8.8% increase in failure load and a 21.8% improvement in stiffness compared to the control slabs. This substitution also had a positive impact on ductility, cracking behavior, and toughness.
7. The addition of 1% steel fiber (SF) in slabs with a 10% glass powder replacement further enhanced the slab's strength by 38.2%. Also, steel fibers were utilized to delay the formation of cracks in the RC slabs.

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