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RESEARCH PAPER

An Experimental Investigation of Flexural Performance of FRP Reinforced Concrete Slabs

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Abstract

In the study, flexural performances of FRP reinforced concrete (RC) slabs with different fiber and bar surface properties were investigated. Glass fiber reinforced polymer (GFRP), Carbon fiber reinforced polymer (CFRP), Aramid fiber reinforced polymer (AFRP) and Basalt fiber reinforced polymer (BFRP) steel reinforcements were used in the reinforcement of the slabs. A total of 27 slabs were produced in the dimensions of 1100–1100–100 mm and with the same reinforcement ratios as FRP and steel reinforcement and were tested with the four-point flexural test method. The flexural strength, moment capacity, toughness and ductility values of the slabs were calculated by determining their flexural behaviour, and the average values were compared. In the comparison, the behaviour of the FRP RC slabs was analysed by taking the steel RC slabs as reference. The effects of FRP fiber type and bar surface properties on slab behaviour were evaluated. The bending load-carrying capacity of AFRP and GFRP RC slabs with ribbed surfaces was 4% higher than those with sand-coated surfaces. In addition, the bending load-carrying capacity of BFRP and CFRP RC slabs with sand-coated surfaces was 13% and 16% higher than those with ribbed surfaces, respectively. The type of failure in slabs varies based on the type of reinforcement and the surface properties of the reinforcement. Three types of failures have been identified: flexural failure, shear failure, and flexural-shear failure. The ductility performance of steel RC slabs has been determined to be the highest, with a value of 9.45. When comparing toughness, sand-coated FRP bars exhibit toughness levels 8–40% higher than ribbed ones. Among the FRP RC slabs, sand-coated CFRP RC slabs provide the greatest contribution to flexural load-carrying capacities.

Keywords Reinforced concrete slab · FRP Bars · Flexural test · Effect of bar surface types · Ribbed surface · Sand-coated surface

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1 Introduction

Steel bars are the main components of reinforced concrete (RC), which is the most widely used construction system today. However, they have some limitations as well as many superior properties. The corrosion of steel bars used with concrete to meet tensile stresses is the main problem frequently seen in RC structures. In addition, alternative options that can be used instead of steel bars are sought for chemical production facilities and structures where a magnetic field is not desired. For these reasons, fiber reinforced polymer (FRP) composite materials have become popular in recent years in the search for alternative reinforcement materials to steel bars in the construction industry. FRP materials are rapidly advancing to become an alternative to many materials in the construction industry thanks to their properties such as strength, durability, lightness, corrosion performance, low thermal conductivity, electrical insulation, and non-magnetic field formation [1]. The use of FRP composites in the construction industry is increasing as they offer many advantages and can be produced in different forms. FRPs can be produced in the form of fabric, profiles, or bars, and this enables them to be used as reinforcement in buildings, structural elements of the carrier system and reinforcement in concrete [2]. It is thought that FRP bars will be used in many applications, such as coastal protection structures, field concrete, concrete roads, bridge decks, and ground concrete.

In recent years, many academic studies have been conducted on the use of FRP bars in concrete and the evaluation of their performance. FRP bars are used as an alternative to steel bars in columns, beams, and slabs in concrete.

Various experimental studies have been carried out using many variables in the researches [3–6] on the use of FRP bars in RC columns. It is seen that mostly GFRP bars are used as FRP reinforcement in the columns, and AFRP, BFRP or CFRP are rarely preferred [7–10].

It is possible to see hybrid beam designs in which fibrous concretes and various fibrous FRP reinforcements are used together in studies on the use of FRP reinforcement in beams [11–15]. There are also studies in which FRP bars are used in T-section beams [16, 17], their effects on shear behaviour of beams [18], their seismic behaviour [19] and their hybrid use with steel reinforcement [20, 21]. In addition, there are also studies analyzing the effects of experimental investigation of the effects of FRP bar fiber type and surface characteristics on the performance of RC beams [22]

Some researchers [23] have made theoretical studies on the new shear strength formula for FRP or steel reinforced two-way concrete slabs. They evaluated the studies on shear estimation in the literature and stated that the shear strength could be found within the safety limits with the formulation they proposed. In their study [24] the punching shear design equation for two-way concrete slabs reinforced with FRP reinforcement and stirrups was investigated. They proposed a design equation for the punching shear strength of two-way slabs reinforced with FRP bars and stirrups. The proposed design equation was calibrated against experimentally measured strengths and had good accuracy. In another study the estimation of the punching shear capacity of FRP reinforced two-way concrete slabs was carried out [25]. The punching shear strength of different types of FRP RC slabs were evaluated. A total of 59 full-size slab test results from the literature were compared with current theoretical predictions.

In a study on one-way concrete slabs with FRP bar [26], the shear resistance of the slabs was studied. A total of 16 one-way RC slabs were produced using steel bars, GFRP and CFRP bars and four-point flexural test method were performed. The structural behaviour of the slabs was investigated in terms of fracture mechanisms, crack patterns, major shear cracks and final capacities. According to the experimental results, it was stated that the use of high strength concrete had a positive effect on the initial shear crack load and final load-carrying capacity. The effect of bar type and diameter on the failure mode of bar shear stiffness was discussed. It was stated that while CFRP RC slabs generally have brittle fractures, similar stiffness occurs in GFRP RC slabs. Some researchers [27] used high fly ash and self-compacting concrete in BFRP reinforced one-way concrete slabs. They performed experimental and theoretical analyses and used variables such as concrete type, polypropylene fiber percentage and BFRP reinforcement percentage. They evaluated the accuracy of the crack load, crack spacing and crack width theoretical models by comparing the experimental results with the predicted results. In another study examining the flexural behaviour of BFRP reinforced one-way slabs [28], the flexural performance of the RC slab was investigated. The study included an experimental investigation and a nonlinear finite element study for seven BFRP concrete slabs. Experimental test results showed that the ultimate flexural loads and behaviour of BFRP RC slabs were better compared to steel RC slabs. In addition, the structural behaviour of the slabs was confirmed by finite element models.

Also [29] the tests of FRP reinforced full-scale concrete bridge slabs were performed by some researchers. They investigated the behaviour of GFRP, CFRP and steel-RC bridge decks under concentrated loads. The slabs were tested by producing a total of eight full-scale slabs, which were 3000 mm long and 2500 mm wide. The experimental parameters were two different slab thicknesses, two strength concrete, two reinforcement ratios and three reinforcement types. In a study in which the fatigue analysis of GFRP RC bridge slabs was determined experimentally [30], six full-size slabs were tested. Different types of reinforcement, ratios and configurations were used. The finite element model was used to investigate the effect of different parameters on the final static capacity. It was stated that GFRP RC slabs had superior fatigue performance compared to steel RC slabs. In the examination of nonlinear finite element analysis of FRP reinforced full-scale concrete bridge slabs [31], a parametric study was conducted by creating 27 nonlinear finite element analysis models with different parameters such as concrete strength, reinforcement type (GFRP, CFRP and steel) and lower transverse reinforcement ratio. It was stated that increasing the concrete compressive strength would increase the ultimate load-carrying capacity and deflection of the slab. On the other hand, in the literature, the static capacity of composite materials and linear elastic fracture mechanics can be calculated with numerical methods [32–34].

In this experimental study, unlike the studies in the literature, steel RC slabs and four different FRP RC slabs were prepared in full scale and tested. In addition, the effects of both FRP bar types and bar surface types on flexural behaviour were evaluated. A total of 27 RC slabs were tested using AFRP, BFRP, CFRP, GFRP and steel bars; the flexural strength, moment carrying capacity, fracture toughness of FRP and steel RC slabs were calculated, and their flexural behaviours were interpreted.

2 Material and Method

2.1 FRP Bars

The investigation includes a flexural test on concrete slabs made with steel and four different FRP bars. AFRP, BFRP, CFRP, and GFRP bars have two different surface properties, sand-coated and ribbed, which are shown in Fig. 1. "R" is used for ribbed surface reinforcement, and "S" is used for sand-coated surface reinforcement.

The fiber ratio of FRP bars was 55% by volume and tensile tests were carried out to determine the mechanical properties of the reinforcements (Fig. 2). Average tensile strengths and specific gravities determined by experimental studies for all bar types are given in Table 1.

It is known that FRP bars have a lower specific gravity than steel bars. It was found that the AFRP, BFRP, CFRP, and GFRP bars utilized in the study were 5.45–4.87–5.30–4.28 times lighter than the steel bar. In addition, a tensile test was done on the bars, and the results are shown in Fig. 3.

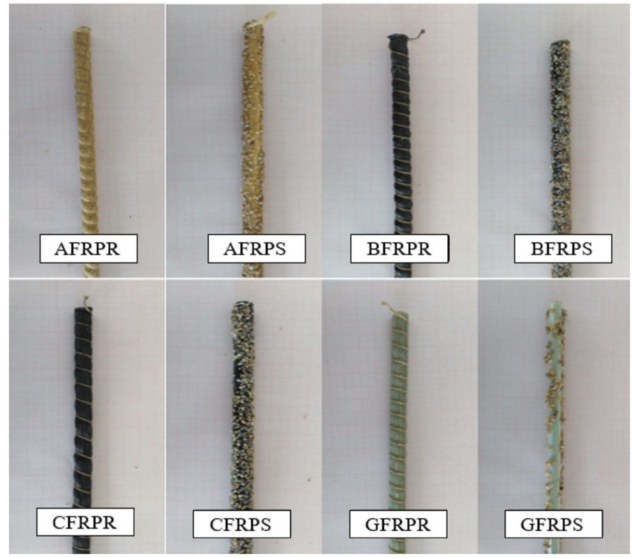


Fig. 1 FRP bar types and surfaces

2.2 Production of the Slabs

The dimensions of the concrete slabs are 1100 × 1100 × 100 mm, the cubic compressive strength of the concrete is 28 MPa. The nomenclature and explanations of 27 RC slabs are given in Table 2. The preparation phases of the slabs are shown in Fig. 4.

2.3 Flexural Test Method of Slabs

RC slabs produced using different bar types and surfaces were subjected to three-point flexural tests. In the flexural tests, the effective span of the slabs was 100 mm and the loading speed was 5 mm/min. The flexural behaviour of the slabs, breaking loads and deflection amounts were determined by using the flexural frame system (Fig. 5).

3 Experimental Results

The results obtained for the slabs formed with each type of reinforcement at the of the three-point flexural test were evaluated and presented. There are 3 different failure modes in slabs: flexural failure, shear failure and flexural-shear failure. The experimental result contains the load–deflection and failure mode information of the slabs.

3.1 Steel RC Slabs

The load–deflection graph representing the visuals and samples of the three slabs produced by using steel bar as a result of the flexural test is given in Fig. 6.

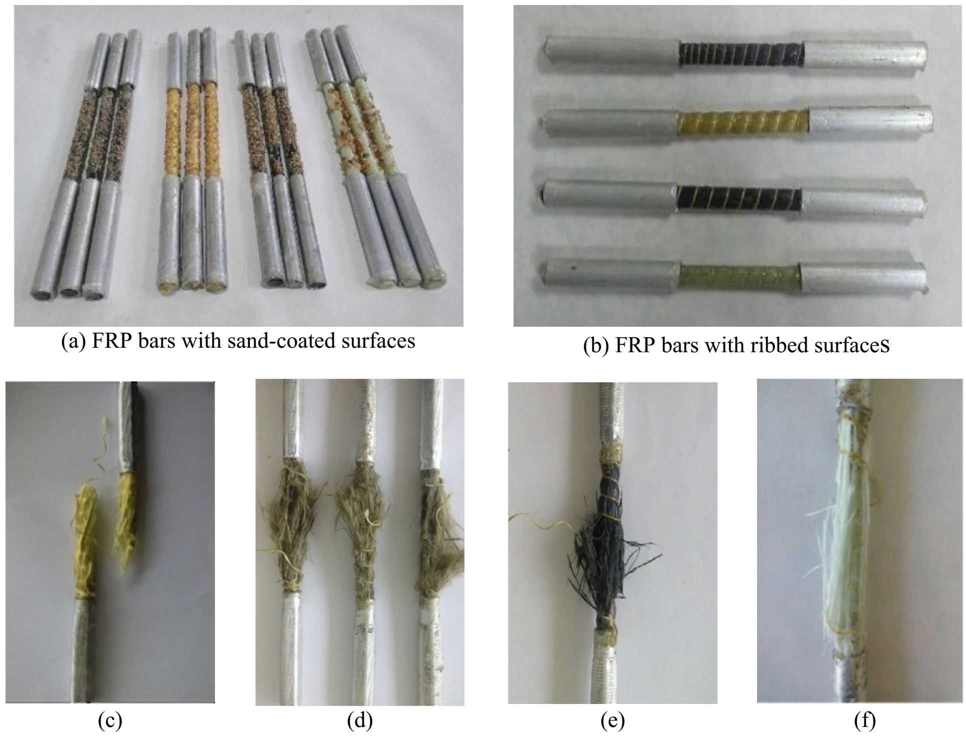


Fig. 2 Before the tensile test of FRP bars **a**, **b** after the test **c** AFRP bar **d** BFRP bar **e** CFRP bar **f** GFRP bar

Table 1 FRP bars average tensile strength and specific gravity values

	Steel bar	AFRP bar	BFRP bar	CFRP bar	GFRP bar
Specific Gravity (gr/cm^3)	7.82	1.44	1.61	1.48	1.83
Tensile Strength (N/mm^2)	599.50	1223.60	1020.80	1304	883.30
Ultimate strain	0.002 (yield)	0.021	0.019	0.011	0.018
Elasticity modulus (N/mm^2)	193.000	58.760	54.700	123.140	48.320

Table 2 Slab specimens' nomenclature

Slab ID	Bar surface	Number of specimen
STEEL	Ribbed	3
AFRPR	Ribbed	3
AFRPS	sand-coated	3
BFRPR	Ribbed	3
BFRPS	Sand-coated	3
CFRPR	Ribbed	3
CFRPS	Sand-coated	3
GFRPR	Ribbed	3
GFRPS	Sand-coated	3

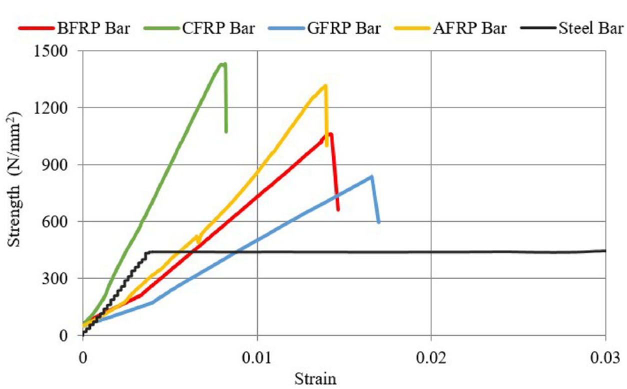


Fig. 3 Stress–strain graphs of FRP bars

When the flexural behaviour of the steel RC slabs was examined, it was concluded that the average flexural load was 175.50 kN, the average displacement value was 29.80 mm, and the failure mode was flexural (Table 3). That failure type means steel bar yields before concrete crushes. This failure mode occurs when the loads on the beam exceed its flexural capacity (Fig. 6a).

3.2 AFRP RC Slabs

The fracture images and load–deflection graphs of AFRPS and AFRPR RC slabs obtained from flexural tests of three

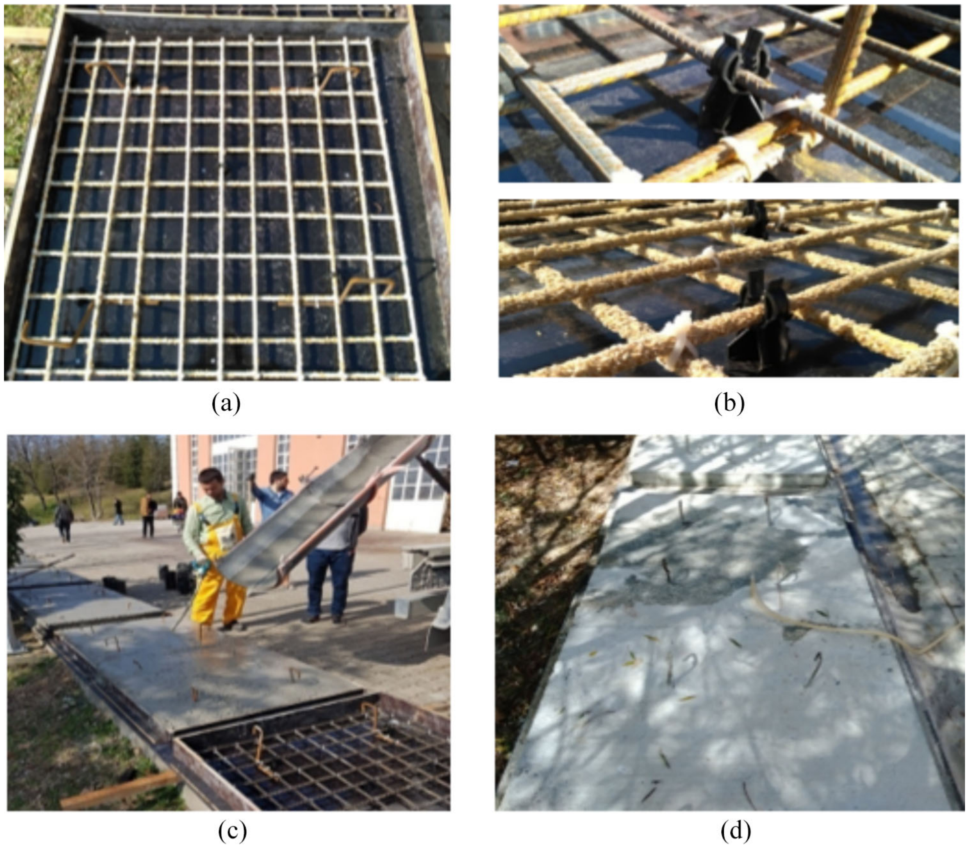


Fig. 4 Preparation of specimens **a** bar arrangement **b** concrete cover detail **c** concrete casting **d** curing of slabs

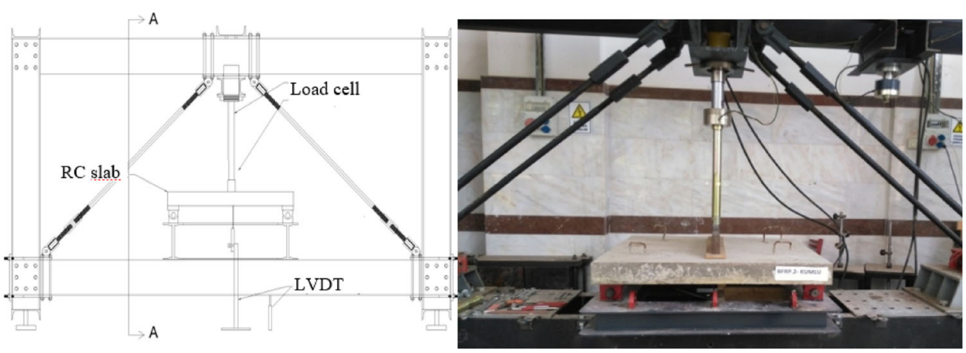


Fig. 5 Test frame system and load applicators

sand-coated and three ribbed AFRP RC slabs are given below. (Fig. 7). The numerical test results and failure modes of the AFRP RC slabs are presented in Table 4.

In the analysis of the flexural behaviour of AFRPS RC slabs, the average flexural load was found to be 152.8 kN, and the average displacement was 15.70 mm (Table 4). These analyses concluded that the failure mode was a combination of flexure and shear. It was observed that the first crack in the concrete of AFRPS RC slabs occurred at a flexural load of 50 kN and a displacement of 2.5 mm. When examining the failure modes of the slabs under the ultimate flexural load, it was determined that after the growth of flexural cracks, shear failure became dominant. In addition, crushes occurred in a part of the concrete where the load was applied (Fig. 7a).

In AFRPR RC slabs, the initial concrete crack in the flexural region occurred at an average load of 40 kN and a displacement of 2.2 mm. The slab experienced sudden failure at an average flexural load of 159.2 kN and a displacement of 16.50 mm (Fig. 7b). The predominant failure mode in the slab is shear failure.

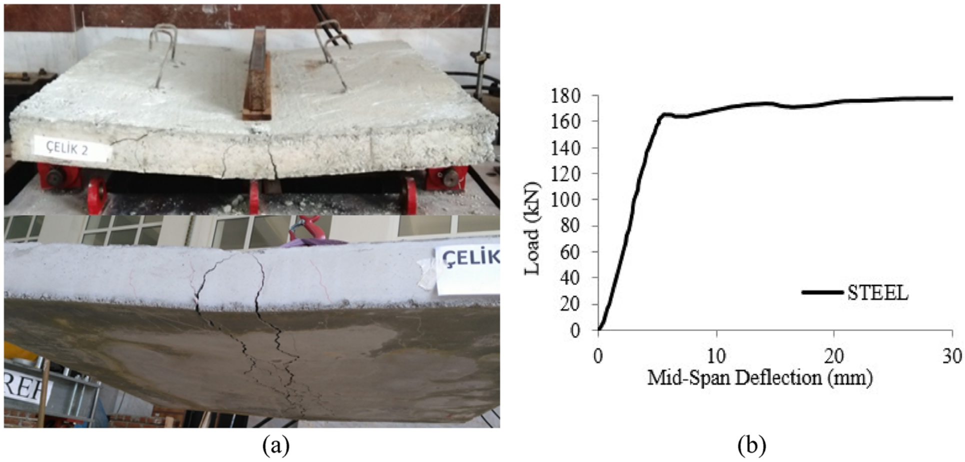


Fig. 6 Three-point flexural test of steel RC slabs **a** failure mode **b** load–deflection curve

Table 3 Flexural test results of steel RC slabs

Slab	Specimen	Ultimate load (kN)	Max. Deflection (mm)	Ave. load (kN)	Ave. deflection (mm)	Failure mode
STEEL	1	173,30	27,30	175,50	29,80	Flexural
	2	177,20	32,00			
	3	176,10	30,10			

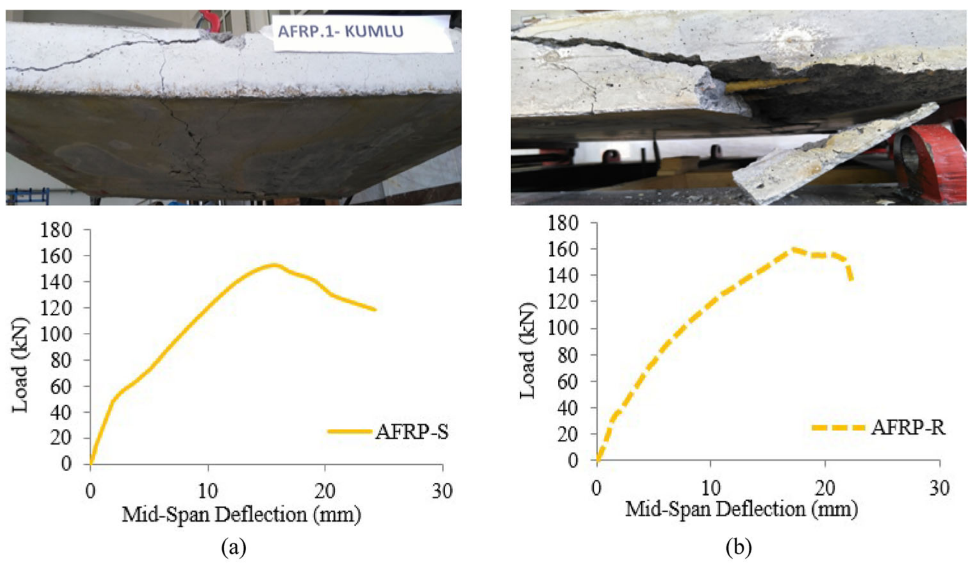


Fig. 7 Three-point flexural test of AFRP RC slabs **a** sand-coated bar **b** ribbed surface bar

3.3 BFRP RC Slabs

The failure images and load–deflection graphs of BFRPS and BFRPR slabs at the end of flexural tests of BFRP RC slabs are given in Fig. 8. The numerical test results and failure modes of the BFRP RC slabs are presented in Table 5.

It was determined that the average flexural load of the BFRPS RC slabs was 179.20 kN, the average displacement was 25.90 mm, and the failure mode was shear (Table 5). The average flexural load of the BFRPR RC slabs was 158.60 kN, the average displacement was 21.80 mm, and the failure mode was flexural (Table 5). The alteration of the surface properties of BFRP reinforcement has significantly impacted the load-bearing capacity and failure

Table 4 Test results of AFRP RC slabs

Slab	Specimen	Ultimate load (kN)	Max. deflection (mm)	Ave. load (kN)	Ave. deflection (mm)	Failure mode
AFRPS	1	148,00	14,25	152,80	15,70	Flexural Shear
	2	158,20	17,10			
	3	152,20	15,70			
AFRPR	1	159,50	17,30	159,20	16,50	Shear
	2	159,70	17,80			
	3	158,40	14,25			

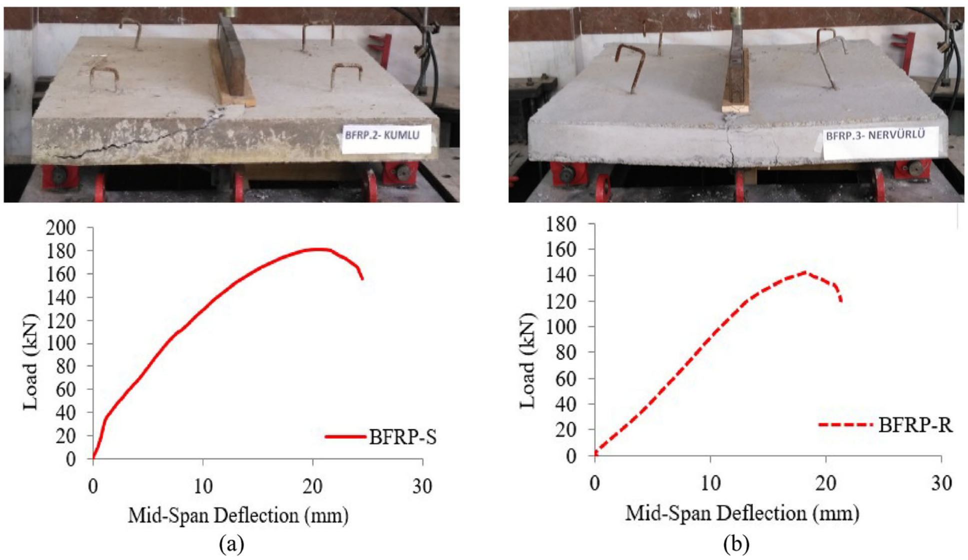


Fig. 8 Three-point flexural test of BFRP RC slabs **a** sand-coated bar **b** ribbed surface bar

Table 5 Test results of BFRP RC slabs

Slab	Specimen	Ultimate load (kN)	Max. deflection (mm)	Ave. load (kN)	Ave. deflection (mm)	Failure mode
BFRPS	1	170,70	37,90	179,20	25,90	Shear
	2	181,40	20,81			
	3	185,60	18,95			
BFRPR	1	174,25	25,20	158,60	21,80	Flexural
	2	142,40	18,10			
	3	159,25	22,08			

modes of the slabs. In BFRPS RC slabs, the predominant failure mode is shear failure, whereas in BFRPR RC slabs, it is flexural failure (Fig. 8a, b).

3.4 CFRP RC Slabs

The failure images and load–deflection graphs of CFRPS and CFRPR RC slabs at the end of flexural tests are given in Fig. 9. The numerical test results and failure modes of the CFRP RC slabs are presented in Table 4.

The average flexural loads of the CFRPS and CFRPR RC slabs were 224.20 kN and 192.40 kN, respectively, with average displacements of 11.50 mm and 10.70 mm (Table 6). The initial cracking load and displacement for the CFRPS and CFRPR RC slabs were found to be 70.5 kN and 2.5 mm, and 50 kN and 2.25 mm, respectively. The predominant failure mode in CFRP RC slabs is shear failure (Fig. 9a, b).

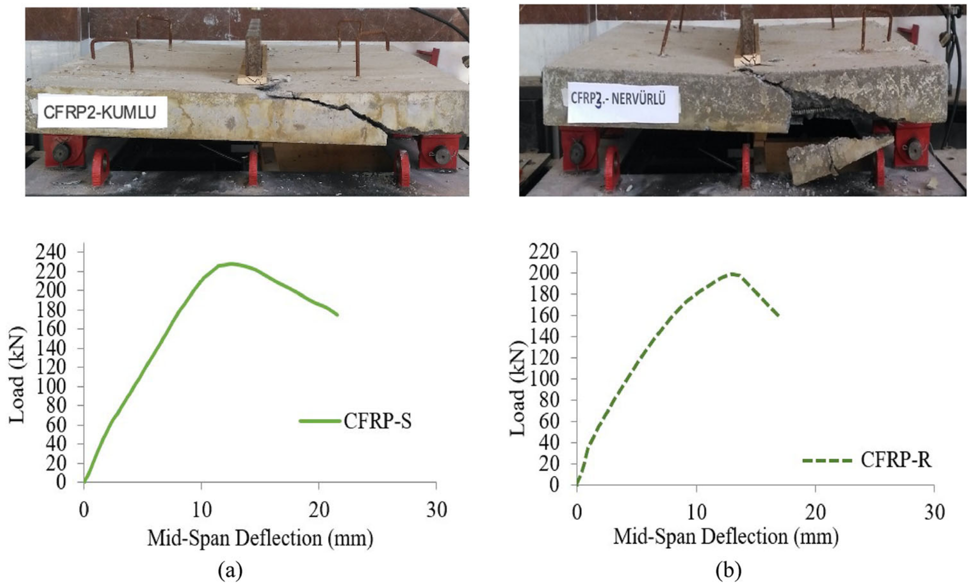


Fig. 9 Three-point flexural test of CFRP RC slabs **a** sand-coated bar **b** ribbed surface bar

Table 6 Test results of CFRP RC slabs

Slab	Specimen	Ultimate load (kN)	Max. deflection (mm)	Ave. load (kN)	Ave. deflection (mm)	Failure mode
CFRPS	1	220,80	10,70	224,20	11,50	Shear
	2	228,20	12,55			
	3	223,70	11,20			
CFRPR	1	188,60	8,70	192,40	10,70	Shear
	2	189,90	10,40			
	3	198,60	13,10			

3.5 GFRP RC Slabs

The failure images and graphics as a result of flexural tests of GFRPS and GFRPR RC slabs are given in Fig. 10. The numerical test results and failure modes of the GFRP RC slabs are presented in Table 4.

Average flexural load of GFRPS RC slabs was 134.80 kN and average displacement was 21.00 mm. Average flexural load of GFRPR RC slabs was 140.80 kN and average displacement value was 19.00 mm (Table 7). The initial cracking load and displacement for the CFRPS and CFRPR RC slabs were found to be 50 kN and 2.1 mm, and 35 kN and 1.75 mm, respectively. The predominant failure mode in CFRP RC slabs is flexural failure (Fig. 10 a-b).

4 Comparison of Slab Behaviours

All slab specimens were tested by the three-point flexural test method under constant velocity loading until failure. Graphs representing the flexural behaviour of the slabs were prepared and the graphs of the slabs with sand-coated reinforcement are presented in Fig. 11.a and the graphs of the slabs with ribbed reinforcement are presented in Fig. 11.b.

When the load–deflection results of RC slabs are examined, steel RC slabs have the highest flexural stiffness and ductility. Among FRP RC slabs, CFRPS and CFRPR RC slabs have the highest flexural stiffness and flexural strength, while GFRPS and GFRPR RC slabs have the lowest flexural stiffness and flexural strength. The flexural stiffnesses' of CFRP RC slabs with ribbed and sand-coated surfaces were similar. The lowest flexural stiffness was obtained in BFRPR RC slabs.

Parameters such as moment capacities, flexural strengths, fracture toughness and ductility of the slabs were prepared and presented in Table 8. Here, Toughness values were calculated using the area under the load–deflection graphs. The ductility of the slabs was obtained by using the displacement values in the load–deflection test results.

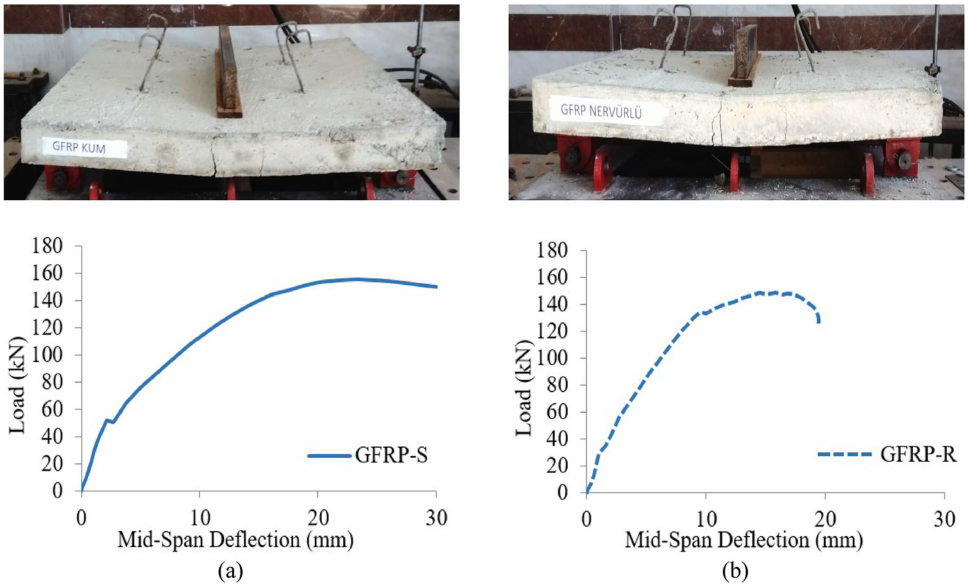


Fig. 10 Three-point flexural test of GFRP RC slabs **a** sand-coated bar **b** ribbed surface bar

Table 7 Test results of GFRPS RC slabs

Slab	Specimen	Ultimate load (kN)	Max. deflection (mm)	Ave. load (kN)	Ave. deflection (mm)	Failure mode
GFRPS	1	155,20	23,36	134,80	21,00	Flexural
	2	114,40	18,57			
	3	134,80	21,00			
GFRPR	1	148,30	15,80	140,80	19,00	Flexural
	2	132,60	22,20			
	3	141,60	19,40			

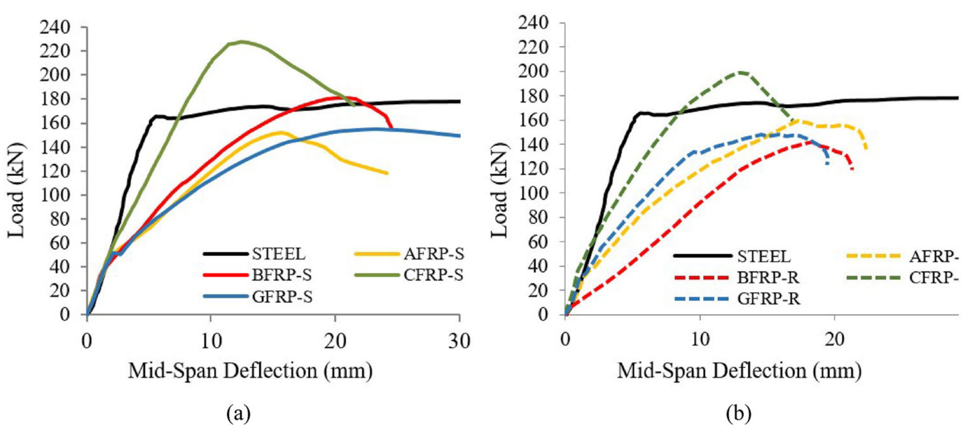


Fig. 11 Load–deflection curves of slabs **a** sand-coated bars **b** ribbed surface bars

4.1 Comparison of Slabs' Flexural Loads

The flexural test results of the slabs were compared by taking the steel slabs as reference. When the flexural load values of all slabs are examined, it is seen that CFRPS reinforced slabs have a 27.7%, CFRPR reinforced slabs have a 9.6% and BFRPS reinforced slabs have a 2.1% higher flexural load than steel reinforced slabs. GFRPS reinforced slabs have the lowest flexural capacity with 23.2% compared to steel-reinforced slabs. This is followed

Table 8 Calculated parameters from experimental data

Slab	Flexural load (kN)	Max. deflection (mm)	Moment capacity (kN.mm)	Flexural strength (kN/mm^2)	Failure toughness (kN.mm)	Ductility	Failure type
STEEL	175,50	29,80	43,90	26,30	4571,00	9.45	Flexural
AFRPS	152,80	15,70	38,20	22,90	1984,20	2.34	Flexural-Shear
AFRPR	159,20	16,50	39,90	23,90	1920,70	1.61	Shear
BFRPS	179,20	25,90	45,90	26,90	2195,80	1.74	Shear
BFRPR	158,60	21,80	39,60	23,75	1637,40	1.48	Flexural
CFRPS	224,20	11,50	56,10	33,60	3180,00	2.30	Shear
CFRPR	192,40	10,70	48,10	28,90	1218,00	1.82	Shear
GFRPS	134,80	21,00	33,70	20,20	1616,60	2.06	Flexural
GFRPR	140,80	19,00	35,10	21,10	1675,10	2.04	Flexural

by GFRPR reinforced slabs with 19.8%, AFRPS reinforced slabs with 12.9%, BFRPR reinforced slabs with 9.6%, and AFRPR reinforced slabs with 9.3%, respectively (Fig. 12).

In the flexural load comparison between steel and sand-coated surface FRP RC slabs, CFRPS RC slabs have the highest flexural load value of 224.20 kN among both sand-coated and ribbed surfaced slabs. This is followed by BFRPS RC slabs with 179.20 kN, steel RC slabs with 175.50 kN, AFRPS RC slabs with 152.80 kN, and GFRPS RC slabs with 134.80 kN (Fig. 12-a).

In the flexural load comparison between steel and ribbed surface FRP RC slabs, CFRPR RC slabs have the highest flexural load value among ribbed surface slabs with 192.40 kN. This is followed by steel RC slabs with 175.50 kN, AFRPR with 159.58, BFRPR with 158.30 kN and GFRPR with 140.50 kN (Fig. 12-b).

4.2 Comparison of Slabs' Moment Capacity

When the moment carrying capacities of the slabs are compared, CFRPS and CFRPR RC slabs have 27.76% and 9.6%, BFRPS RC slabs have a 2.10% higher capacity than steel RC slabs. GFRPS RC slabs have the lowest moment carrying capacity of 23.2% compared to steel RC slabs. This is followed by GFRPR RC slabs with 19.95%, AFRPS RC slabs with 12.94%, BFRPR RC slabs with 9.80% and AFRPR RC slabs with 9.07%, respectively (Fig. 12).

CFRPS slabs have the highest moment capacity with 56.10 kN.m, while the moment capacity of BFRPS RC slabs is 44.80 kN.m. These values are followed by steel RC slabs with 43.90 kN.m, AFRP RC slabs with 38.20 kN.m and GFRPS RC slabs with 33.70 kN.m (Fig. 12-c).

When comparing the moment capacities of steel and ribbed surface FRP RC slabs, CFRPR slabs have the highest moment capacity among ribbed surfaces with 48.10 kNm. Steel, AFRPR, BFRPR and GFRPR RC slabs follow this with values with 43.90 kNm, 39.90 kNm, 39.60 kNm and 35.10 kNm, respectively (Fig. 12d).

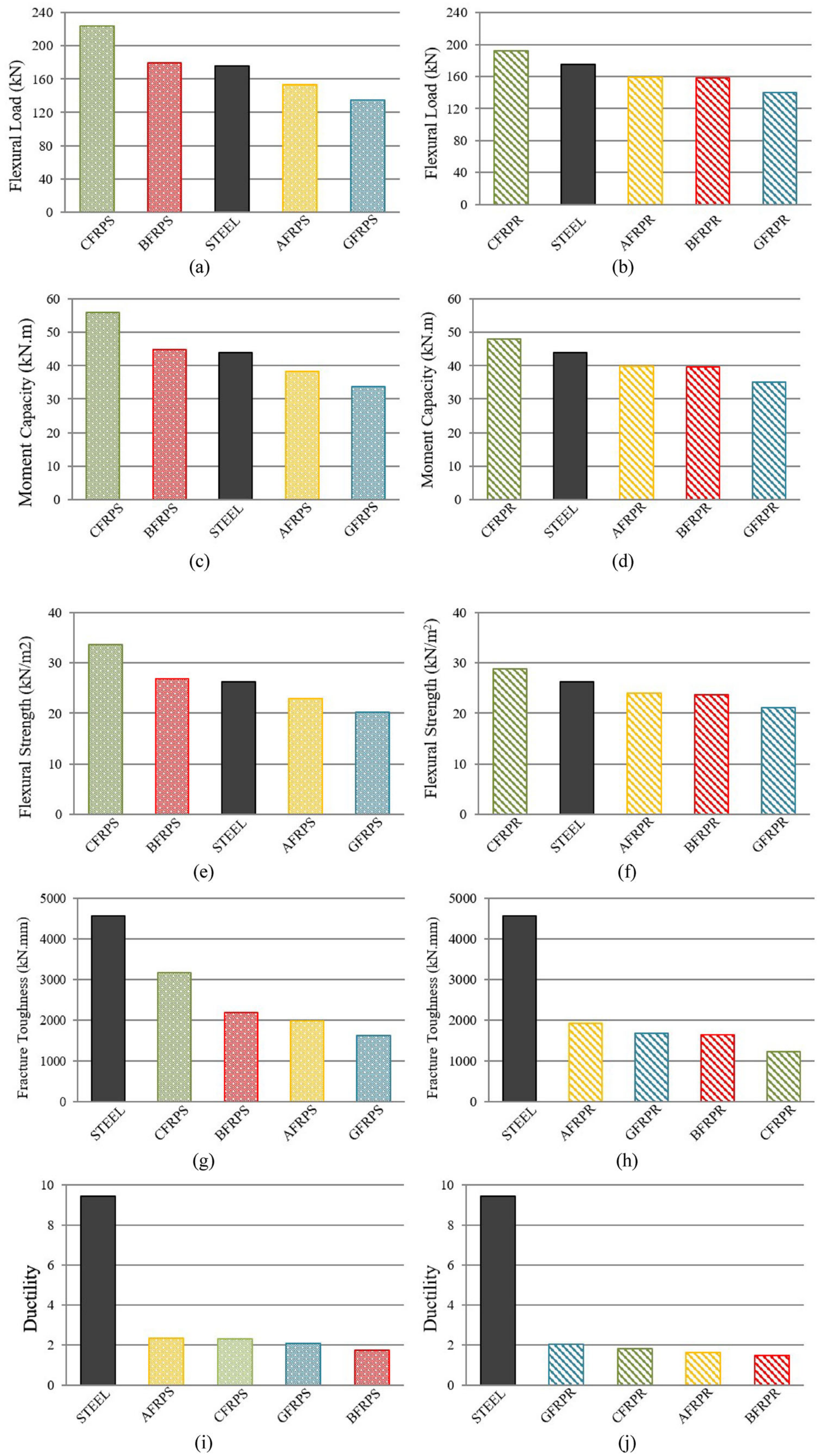
4.3 Comparison of Slabs Flexural Strength

When the flexural strength values of the slabs are examined, the percentage ratios are the same as the results of flexural load and moment capacity. CFRPS RC slabs have a higher flexural strength than steel RC slabs with a rate of 27.80%. The lowest flexural strength compared to steel RC slabs was obtained in GFRPS RC slabs with 23.2% (Fig. 12).

In the flexural strength comparison between steel and sand-coated FRP RC slabs, CFRPS RC slabs have the highest flexural strength with 33.60 kN/m^2. This is followed by BFRPS RC slabs with 26.90 kN/m^2, steel RC slabs with 26.30 kN/m^2, AFRPS RC slabs with 22.90 kN/m^2, and GFRPS RC slabs with 20.20 kN/m^2 (Fig. 12e). In the comparison of the flexural strength of ribbed surface FRP RC slabs, CFRPR RC slabs have the highest flexural strength among ribbed surface bars with 28.90 kN/m^2. The flexural strengths of steel RC, AFRPR, BFRPR and GFRPR RC slabs are 26.30 kN/m^2, 23.90 kN/m^2, 23.75 kN/m^2 and 21.10 kN/m^2, respectively (Fig. 12f).

4.4 Comparison of Slabs' Fracture Toughness

In comparison of toughness energies, the highest value was obtained in steel RC slabs. Compared to steel RC slabs, the lowest toughness value of was obtained in CFRPR RC slabs with 73.35%. It is followed by GFRPS RC slabs with 64.60%, BFRPR with 64.20%, GFRPR with 63.35%, AFRPR with 58%, AFRPS with 56.60%, and BFRPS with 52%, respectively. CFRPS RC slabs, which have the highest toughness energy among FRP RC slabs, have 30.40% lower toughness than steel RC slabs (Fig. 12).


Flexural Load (kN)
CFRPS
BFRPS
STEEL
AFRPS
GFRPS
(a)
Flexural Load (kN)
CFRPR
STEEL
AFRPR
BFRPR
GFRPR
(b)
Moment Capacity (kN.m)
(c)
Moment Capacity (kN.m)
(d)
Flexural Strength (kN/m2)
(e)
Flexural Strength (kN/m²)
(f)
Fracture Toughness (kN.mm)
(g)
Fracture Toughness (kN.mm)
(h)
Ductility
(i)
Ductility
(j)

◀ **Fig. 12** Comparison of slabs' flexural loads **a** sand-coated bar slabs **b** ribbed bar slabs, moment capacity **c** sand-coated bar slabs **d** ribbed bar slabs, flexural strength **e** sand-coated bar slabs **f** ribbed bar slabs, fracture toughness **g** sand-coated bar slabs **h** ribbed bar slabs, ductility **i** sand-coated bar slabs **j** ribbed bar slabs

When the toughness between steel and sand-coated FRP RC slabs is compared, the steel RC slab has the highest toughness with 4571 kNmm. CFRPS, BFRPS, AFRPS and GFRPS RC slabs have mean toughness energies of 3180 kNmm, 2195.80 kNmm, 1984.20 kNmm and 1616.60 kNmm, respectively (Fig. 12g).

When the toughness values between steel RC slabs and ribbed surface FRP RC slabs are examined, AFRPR, GFRPR, BFRPR and CFRPR RC slabs follow with 1920.70 kNmm, 1675.10 kNmm, 1637.40 kNmm and 1218 kNmm, respectively. Steel slabs have higher toughness than ribbed surface FRP RC slabs (Fig. 12h).

4.5 Comparison of Slabs Ductility

Similar to the toughness results, steel RC slabs have the highest ductility. BFRPR RC slabs have 84.30% lower ductility compared to steel RC slabs. This is followed by AFRPR RC slabs with 83%, BFRPS with 81.60%, CFRPR with 80.70%, GFRPR with 78.40%, GFRPS with 78.20% and CFRPS with 75.70%, respectively. AFRPS RC slabs, which have the highest ductility among FRP RC slabs, have 75.20% lower ductility than steel RC slabs (Fig. 12).

When the ductility between steel RC slabs and sand-coated FRP RC slabs is compared, the steel RC slabs have the highest ductility with 9.45. AFRPS, CFRPS, GFRPS, and BFRPS RC slabs have mean ductility values of 2.34, 2.30, 2.06, and 1.74, respectively (Fig. 12i).

When comparing FRP reinforced slabs with ribbed surfaces, the ductility values of GFRPR, CFRPR, AFRPR, and BFRPR RC slabs are 2.04, 1.82, 1.61, and 1.48, respectively (Fig. 12j).

5 Conclusions and Recommendations

The load–deflection graphs, moment capacity, flexural strength, fracture toughness and ductility results obtained at the end of flexural tests with sand-coated and ribbed surfaced FRP RC slabs are summarized below:

- Compared to steel RC slabs, which have a flexural load-carrying capacity of 175.50 kN, CFRPS, CFRPR, and BFRPS RC slabs exhibit higher capacities by 18.3%, 9.6%, and 2.1%, respectively, while GFRPS, GFRPR, AFRPS, BFRPR, and AFRPR RC slabs show lower capacities by 23.2%, 19.95%, 12.94%, 9.80%, and 9.07%, respectively.
- The steel RC slabs attained the highest toughness value. Despite CFRPS RC slabs exhibiting a 30.40% lower toughness compared to steel RC slabs, they have the highest toughness among FRP RC slabs. In contrast, BFRPS, AFRPS, AFRPR, GFRPR, BFRPR, and CFRPR RC slabs exhibit lower toughness energies than steel by 52%, 56.60%, 58%, 63.35%, 64.20%, and 73.35%, respectively.
- When the ductility results of the slabs are examined, the steel RC slabs, considered as the reference, exhibited the highest ductility value. It was observed that the ductility values of FRP RC slabs were 84–78% lower than those of steel RC slabs.
- While the highest stiffness among the slabs was obtained in the steel RC slabs, it was seen that the CFRP RC slabs showed a stiffness close to the steel RC slabs in the linear area. It was observed that the contribution of sand-coated FRP bars to slab stiffness is higher than that of ribbed surface FRP bars.
- The analysis of failure types unveils distinct characteristics across different types of RC slabs. Among these, Steel, BFRPR, GFRPS, and GFRPR RC slabs exhibit flexural failure, while AFRPS RC slabs uniquely display flexural-shear failure. On the other hand, AFRPR, BFRPS, CFRPS, and CFRPR RC slabs primarily experience shear failure.
- As a result of the study, it was determined that the flexural load, flexural moment, flexural strength, toughness, and ductility results of the CFRPS RC slabs were the highest among the FRP RC slabs, and shear type was failure. Among the slabs with flexural failure type, it was determined that the slabs with GFRPR bars provided the highest contribution to the flexural behaviour.
- The study concluded that among FRP RC slabs, CFRPS RC slabs exhibited the highest flexural load, flexural moment, flexural strength, toughness, and ductility results, with a predominant shear failure type. Regarding slabs experiencing flexural failure, those reinforced with GFRPR bars demonstrated the most significant contribution to flexural behaviour.

It has been observed in our study that using different surface and different types of FRPs with the same reinforcement ratio alters the failure types of RC slabs. Further experimental research is required to identify the limit states of shear failure, an undesirable condition in RC elements. Additionally, studies can be conducted to investigate how the type and surface properties of FRPs affect the behaviour of slabs produced with different concrete strength classes, and the effect of FRP reinforcement ratio on the flexural behaviour of RC slabs can be examined. Determining the cost-effectiveness of FRP reinforcement types in RC slabs and exploring economic solution proposals are also important.

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