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Effect of Crimped Steel Fiber Ratios on Punching Shear Strength of Lightweight Concrete Slabs

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Abstract

Punching shear failure is an unfavorable failure mechanism that happens abruptly with little displacement in reinforced concrete flat slabs subjected to focused stress. A localized punching failure in one column increases the shear force acting on the surrounding columns. This could cause the adjoining columns to also experience a punching failure, ultimately resulting in the progressive collapse of the entire structure. In a way akin to a chain reaction, progressive collapse is the term used to characterize the propagation of an initial local failure within a structure, which may lead to a partial or complete collapse. This paper aims to investigate the impact of steel fiber on the punching shear of lightweight slabs. Three slabs measuring 750 x 750 x 70 mm are created. Two percentage of crimped steel fiber are using the volume of steel fiber was (0.5, 1) %. The results showed It can be seen that the ultimate load capacity was increased by (47.36) and (76.05) respectively. For sample content (0.5 and 1) steel fiber compare to control slab (S1-L-W). The results showed that the use of crimped steel fiber improved the first crack load by (84, 182.9) % for slabs used crimped steel fiber. Overall, the findings of this study indicate that adding the crimped steel fibers have significantly increased the ultimate load capacity, Ductility and toughness of the tested RLWC slabs.

1. Introduction

The structural component of the building that provides the floors and ceiling is the reinforced concrete slab. The loads are conveyed directly to the concrete columns in flat slabs, which are reinforced concrete slabs that typically do not contain girders or beams [1]. There are four types of flat slabs: those with a column head, those with a drop panel, those without a column head and a drop panel, and those that have both a drop panel and a column head [2]. Another name for it is a beamless slab system. Due to the building space's versatility and ability to provide higher clear-celling heights, it is extensively utilized in the industry. Since there are no beams, installing sprinklers, pipelines, and other utilities is simple [3]. Furthermore, a level slab has a pleasing appearance, and its formwork is Flexural reinforcement is arranged in an easy-to-understand manner and is therefore not expensive. Compared to the traditional slab with beams, this approach is more cost-effective since it lowers the slab's self-weight on the columns and foundations [4]. When reinforced concrete flat slabs are subjected to focused force, punching shear failure is an undesired failure mode that happens quickly with little displacement.

A localized punching failure in one column increases the shear force acting on the surrounding columns. This could cause the adjoining columns to also experience a punching failure, ultimately resulting in the progressive collapse of the entire structure. In a way akin to a chain reaction, progressive collapse is the term used to characterize the propagation of an initial local failure within a structure, which may lead to a partial or complete collapse. Following the initial breakdown, the structure looks for other load paths so that the neighbouring, undamaged components can take up the load that was previously carried by the injured portions. It is possible that the latter is not strong enough to withstand the extra stresses, therefore more load redistribution will probably happen until the equilibrium condition is attained [5]. Since the 1960s, fiber-reinforced concrete has emerged as a cutting-edge alternative to the more conventional stirrup-based reinforcement strategy.

Fiber-reinforced concrete (FRC) has been widely used as a prophylactic strategy to avoid bond failure in highly stressed regions of a structure (such as beam-column joints, column bases, and beam midspans) [6].

Fiber reinforced concrete (FRC) is a composite construction material made up of short, discontinuous, and randomly distributed fibers within the concrete. The most common kind of fiber used in reinforced concrete is steel fiber (SF). By bridging the fractures in the concrete structure, steel fiber increases punching shear, flexural stiffness, moment resistance, ductility, and ultimate shear strength while decreasing crack widths and spacing [7, 8].

While steel fiber has been used extensively in the last several decades to enhance the performance of structural components, current studies are investigating the use of fiber combinations in cementitious composites. This multi-fiber approach's main goal is to reduce cementitious material cracking under a variety of loading scenarios and strain amplitudes [9, 10]. Rather than the thickness of the slab, the length of the slab determines the punching shear strength [11]. A significant portion of the overall load on the structure is supported by the self-weight of concrete construction.

Thus, there are clear benefits to reducing the density of concrete. The advantages of lightweight concrete (LWC) in terms of both economy and practicality have made it one of the most important building materials of today [12]. Normal concrete has a self-weight of between 2,400 and 2,500 kg m−3, which make it quite heavy, the overall dead load causes structural elements to enlarge in size. Concrete that has both an expanding agent and lightweight aggregate (LWA) is known as LWC concrete.

In this work, light weight concrete (LWC) was utilized to reduce the weight of reinforced concrete, which is thought to be a useful solution for the slab-column connection issue. When used to produce concrete, lightweight aggregate has several benefits, including reduced dead load of structural elements, which can lead to a smaller foundation and more available space because columns, slabs, and beams have smaller dimensions; it also improves fire resistance and offers high thermal and sound insulation [13]. The 28-day compressive strength must exceed 17 MPa for structural LWC applications [14]. [15]. These days, a wide variety of LWA, including expanded clays, slate, shale, pumice, and others, can be used to create lightweight concrete. Light expanded clay aggregate (LECA), a type of artificially generated LWA, is one of the LWA types used in the construction of structures. It is made by expanding natural clay in a horizontal rotary kiln at a temperature of approximately 1,200°C (2,190°F).

The heating process causes thousands of small bubbles to develop, which causes the clay to expand.

Roughly, 5-7 times its initial volume, creating a structure akin to a honeycomb [16]. With a 25% step, the replacement percentage of typical aggregate spans from 0% to 100%. The findings indicate that when the LECA level rose, the compressive strength dropped. When 28 days of curing were completed, the flexural strength, split tensile strength, and compressive strength dropped by 16.87, 17.20, and 13.29%, respectively. There was also a weight reduction of roughly 28% with 100% LECA substitution of regular aggregate. Even yet, there is a very slight reduction of strength at 25% LECA substitution. Materials including silica fume, fly ash, slag, steel fiber, and polypropylene fiber can be added to concrete containing LECA to strengthen it and improve its mechanical qualities [17].

2. Materials

Portland cement, silica fume, steel fiber, lightweight expanded clay aggregate (LECA) in place of coarse aggregate, and superplasticizer, are the components use in this study. Every material was examined in compliance with ASTM standard guidelines [20-23]. The primary method of reinforcing the slabs was by the use of deformed steel bars, measuring Ø10 mm. Tensile testing was carried out in compliance with ASTM A615. 1.1% of the total steel utilized in this investigation was divided into two ratios (0.5 and *1*)*%*. Steel fiber that has been crimped The geometry of the crimped steel fiber utilized in current study is depicted in Figure 4, The material properties of Table 1 and Table 7 list the attributes of the steel reinforcement and the fiber employed in this investigation.

Table 1: *Material properties*

Material	Description
Cement	Portland cement (PS). type II
Sand	Natural sand of 4.75 mm max. size
coarse aggregate	lightweight expanded clay aggregate (LECA) max size 10 mm
silica fume	sika fume (HR)
Superplasticizer	sikaviscocrete-171iq
crimped steel	length35 (mm)
fiber	diameter 0.5 (mm)
Water	clean tap water

2.1 Cement

In the present investigation, Portland cement was used. Portland cement's chemical and physical characteristics are displayed in Tables 2 and 3, respectively. According to ASTM C150/C150M-21 the qualities of cement are compliant.

Table 2: *Chemical Composition of Cement*

No.	**Chemical** characteristic	**Tested** cement %	**ASTM** C**150**
1	SiO_2	21.4	--
2	CaO	59.7	--
3	MgO	3.15	≤ 5
4	Fe_2O_3	4.5	--
5	Al_2O_3	3.9	--
6	SO_3	1.9	≤ 2.8
7	Loss on ignition	2.9	≤ 4
8	Insoluble residue	1.22	≤ 1.5
9	Lime Saturated Factor	0.8665	0.66-1.02
10	C_3A	2.7	≤ 5

Table 3: *Physical Characteristics of Cement*

Physical Characteristics	**Tested** Cement	**Specification** limits **(ASTM** C**150)**
Vicat initial time of setting (min)	110	Not less than 45 min
Vicat final time of setting (min)	150	Not more than 375 min
Average compressive strength, Age (3 days), Mpa	16	≥ 8
Average compressive strength, Age (7 days), Mpa	23	≥ 15

2.2 Fine aggregate

For the LWC combination, the readily available natural fine aggregate (sand) with a maximum size of 4.75 mm was utilized. The test findings satisfy ASTM C33/C33M-13 criteria (ASTM, 2013a). Table 4 and Figure 1 display the sand gradation and sulphate.

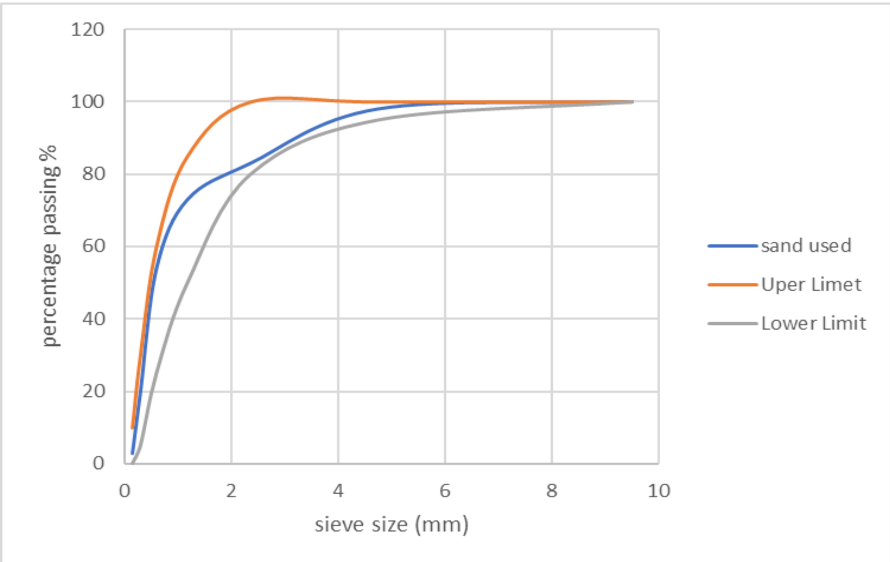

Fig. 1. *Fine aggregate grading curve*

***Table 4**: Grading of Fine Aggregate and Sulphate Content*

No.	**Sieve** Size (**mm)**	**Cumulative** passing %	**Limit** of ASTM C**136/C136M**
1	9.5	100	100
2	4.75	98	95-100
3	2.36	83	80-100
4	1.18	73	50-85
5	0.6	54	25-60
6	0.3	20	5-30
7	0.15	3	0-10
8	Pan	---	---
9	Sulphate	0.5	≤ 0.5%

2.3 Lightweight expanded clay aggregate (LECA)

In this investigation, the LECA was utilized as a lightweight aggregate in all LWC combinations, with a maximum size of 10 mm. In this investigation, the coarse aggregate was completely replaced with expanded clay aggregate, as seen in Figure 2. The test findings satisfy ASTM C330/C330M-17A criteria. Table 5 with Figure 3 and Table 6 list the grading and physical characteristics of the LECA test findings, respectively.

***Fig. 2** lightweight expanded clay aggregate (LECA) used in the current study*

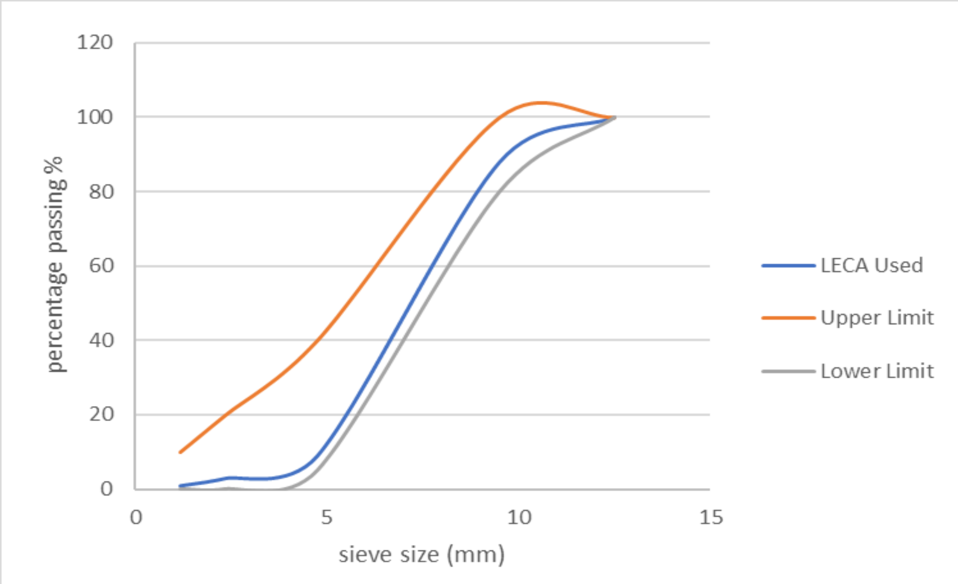

Fig. 3. *Sieve analysis of LECA*

Table 5: *LECA gradation results*

No.	**Sieve** Size **(mm)**	**Cumulative** passing %	**Limit** of ASTM **C136/C136M**
1	12.5	100	100
2	9.5	88	80-100
3	4.75	9	5-40
4	2.36	3	0-20
5	1.18	1	0-10

Table 6: *Physical properties of LECA*

No	**Physical** properties	**Value**
1	Dry density (Kg/m^3)	415
2	Absorption (%)	20
3	Specific gravity	0.62
4	Max. Size(mm)	10

Fig. 4. *Crimped steel fiber*

Table 7: *Properties of steel fiber and steel reinforcement bar*

Material	Property	Value/Description
	Bar diameter [mm]	10
	Yield stress [MPa]	524.14
Steel bar	Ultimate stress [MPa]	635
	Elongation [%]	12
Steel fiber	Diameter [mm]	0.5
	Aspect ratio (L/D)	70
	Tensile strength [MPa]	1150
	Geometry	Crimped

3. Experimental program

Three slabs measuring 750 x 750 mm and 70 mm thick were created. Every model had the same flexural reinforcement; slabs with an upper and lower layer measuring 6 by 10 did not have shear reinforcement. For each slab specimen, three concrete cubes measuring 150 mm by 150 mm by 150 mm, two cylinders measuring 300 mm by 150 mm, and one prism measuring (500 mm * 150 mm * 100 mm) were cast simultaneously with the slabs to estimate the modules of rupture, splitting tensile stress, and stress-strain relationship, respectively. The slabs' dimensions and details of reinforcement are displayed in Figure 5 and Table 8.

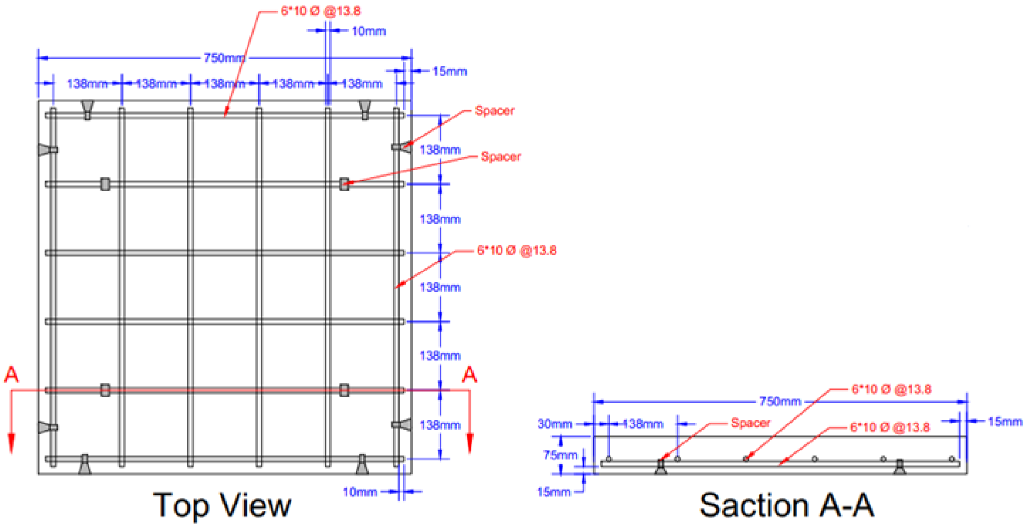

__Fig. 5.__ Details of the specimen

Table 8: *Details of specimen*

No.	Slab Symbol	Type of Fibers	V.f of fibers (%)
1	S1-L.W	No fiber	0
2	S2	Steel fiber (crimped)	0.5
3	S3	Steel fiber (crimped)	1

4. Mix design

To find the mixture ingredient proportion that would satisfy the necessary compressive strength and density for lightweight concrete, numerous experimental mixes were created. Owing to the LECA's high water absorption capacity, more water was added to guarantee the slump kept within the range of 20–100 mm. Specifically, 20% more water was added to the light expanded clay aggregate weight than was used in the control mix. After 28 days, the control concrete mixture should have a compressive strength of roughly 23 MPa. All of the mixes had 460 kg/m^3 of cement. Light expanded clay aggregate (LECA), which was utilized as the coarse aggregate, with a maximum size of 10 mm. Contents of the Mix utilized in this Work, Table 9.

Table 9: *Details of mix properties*

Mix	Cement	sand	LECA	Water	Super plasticizer %
S1	460	936	180	190	1.25

5. Test Setup

The University of Thi-Qar Department of Civil Engineering hosted the tests. The slab specimens were supported by an extremely robust steel frame made of H-sections and a hollow structural section (HSS) that measured 40 mm in width. A universal machine with a 190 kN capacity applied the load. The applied force from the machine to the sabs was transversed using a rigid steel box (60 mm x 60 mm). The mid-span deflection of the slabs was measured using a single dial gauge that was mounted on the slab's bottom surface. Figure 6: The slab test setup is displayed.

Fig. 6. *Process of punching shear test of slabs*

6. Results and discussion

Slabs, Cube, Prism, and Cylinder specimens were tested 28 days after casting.

6.1 Mechanical properties

6.1.1 Compressive Strength (fcu)

Results compressive strengths of cubes are shows in Table 10 and figure 7. It can be seen the addition of two percenters of crimped steel fiber (0.5, 1) % led to improve the compressive strengths by (20.68, 29.89), compared with reference symbol.

Table 10: *Average compressive strength*

No.	Slab Symbol	Type of Fibers	V.f of fibers (%)	Compressive strength	%Increase Compared to lightweight Concrete
1	**S1-L. W**	No fiber	0	29	0
2	**S2**	Steel fiber (crimped)	0.5	35	20.68
3	**S3**	Steel fiber (crimped)	1	37.67	29.89

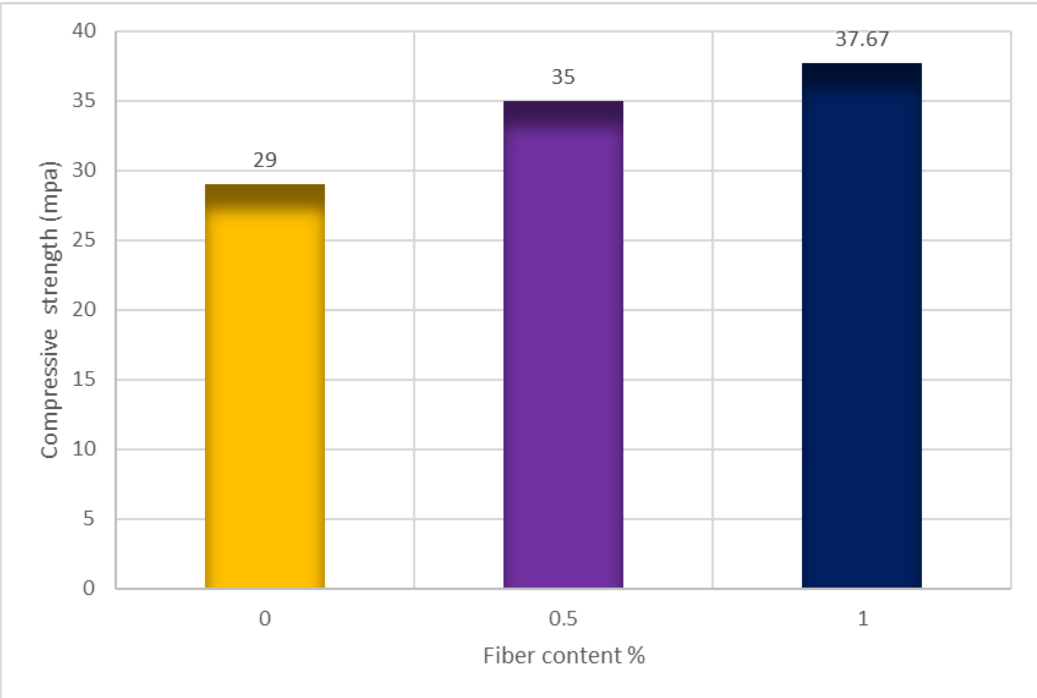

Fig. 7. *Average compressive strength of mixes*

6.1.2 Splitting Tensile Strength

Table 11 and Figure 8 demonstrate that tensile strength values rose as the crimped steel fiber ratio increased. The splitting tensile strength of mixtures is significantly impacted by the addition of crimped steel fibers. There is a clear benefit to adding fiber. When 0.5% and 45.85% of crimped steel fiber were added to a mix, the splitting tensile strength improved by 32.48% compared to the control mix. The combination containing 1% of crimped steel fiber showed the biggest improvement in splitting tensile strength.

Table 11: *Splitting tensile stress (MPa) FSP*

No.	Slab Symbol	Type of fibers	V.F of fibers (%)	Splitting tensile stress (MPa) FSP	%Increase Compared to normal Concrete
1	**S1-L-W**	No fiber	0	2.05	0
2	**S2**	Steel Fiber (crimped)	0.5	2.716	32.48
3	**S3**	Steel fiber (crimped)	1	2.99	45.85

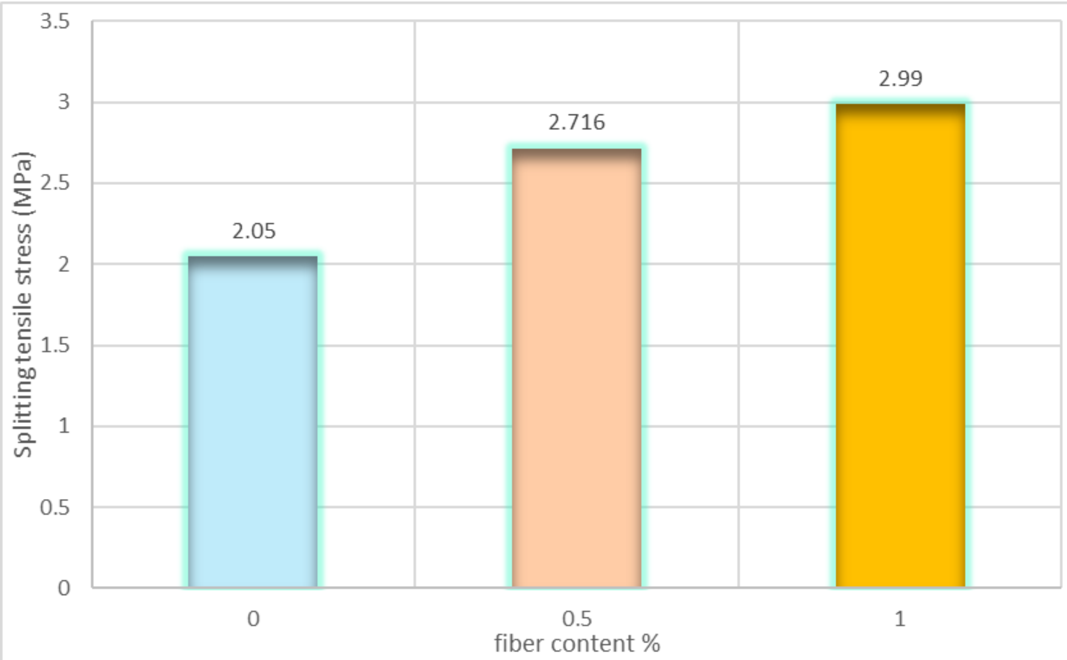

Fig. 8. *Splitting tensile strength*

6.1.3 Modulus of rupture (Flexural strength)

Utilizing concrete prisms measuring 100 x 100 x 500 mm, the flexural strength was determined. Table 12 displays the flexural strength of prisms for LWAC. Figures 9 and 10 show the flexural strength and growth in flexural strength of concrete prisms together with the modes of failure. In general, the modulus of rupture (fcr) increased when crimped steel fibers were added to the lightweight concrete mix. Flexural strength was increased by (75.3) and (139.2)%, respectively, with Vf of (0.5 and 1)% to LWC. This increase varies depending on the kind and percentage of additional crimped steel fiber.

Table 12: *Modules of rupture*

No.	Slab Symbol	Type of Fibers	V.f of fibers (%)	Modules of rupture (MPa) Fcr	%Increase Compared to normal Concrete
1	S1-L-W	No fiber	0	4.13	0
2	S2	Steel Fiber (crimped)	0.5	7.24	75.3
3	S3	Steel fiber (crimped)	1	9.88	139.2

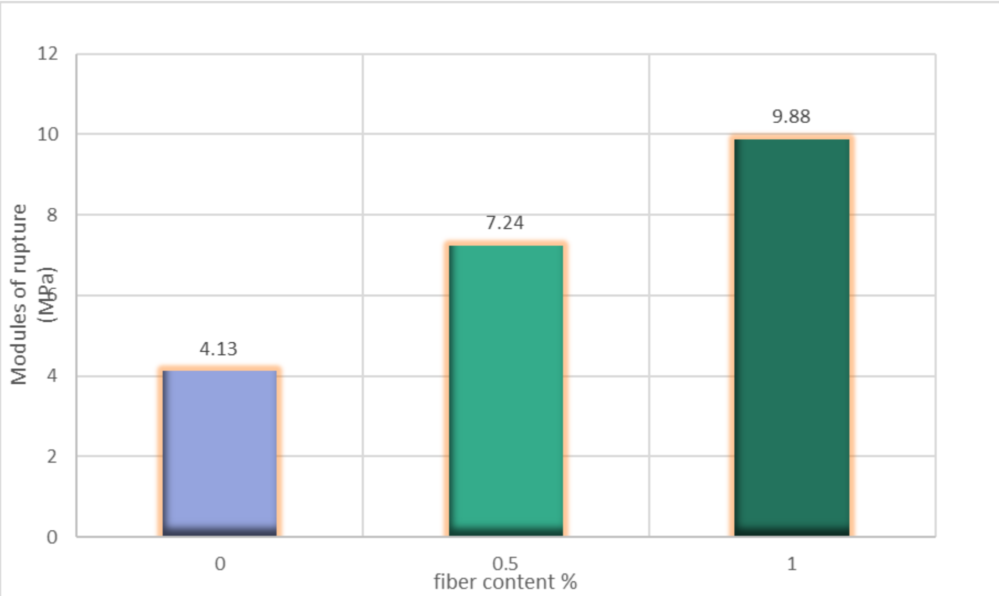

Fig. 9. *Modules of rupture*

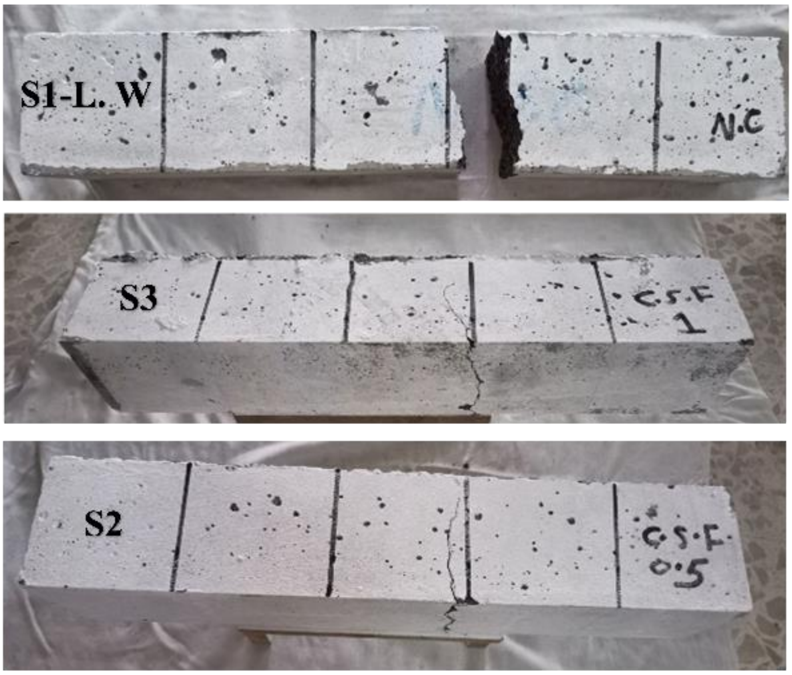

Fig. 10. *Prism specimens and failure shapes*

6.2 Ultimate load and first crack Load

The maximum deflection, initial crack load, and ultimate load capacity were noted in Table 13 and figure 11. It is evident that there was an increase of 47.3 and 76.5 percent in the ultimate load capacity, respectively. For S2 and S3 in comparison to the control slab (S1-L-W) using volume fractions of 0.5% and 1% for crimped steel fiber.

Table 13: *Ultimate load and first crack load of slab specimen*

No.	Slab Symbol	Type of Fibers	Vf of fibers (%)	Ultimate load (KN)	First crack load [KN]	Ultimate deflection (mm)
1	**S1-L-W**	No fiber	0	57	32.6	8.2
2	**S2**	Steel Fiber (crimped)	0.5	84	60	11
3	**S3**	Steel fiber (crimped)	1	100.35	92.25	11.3

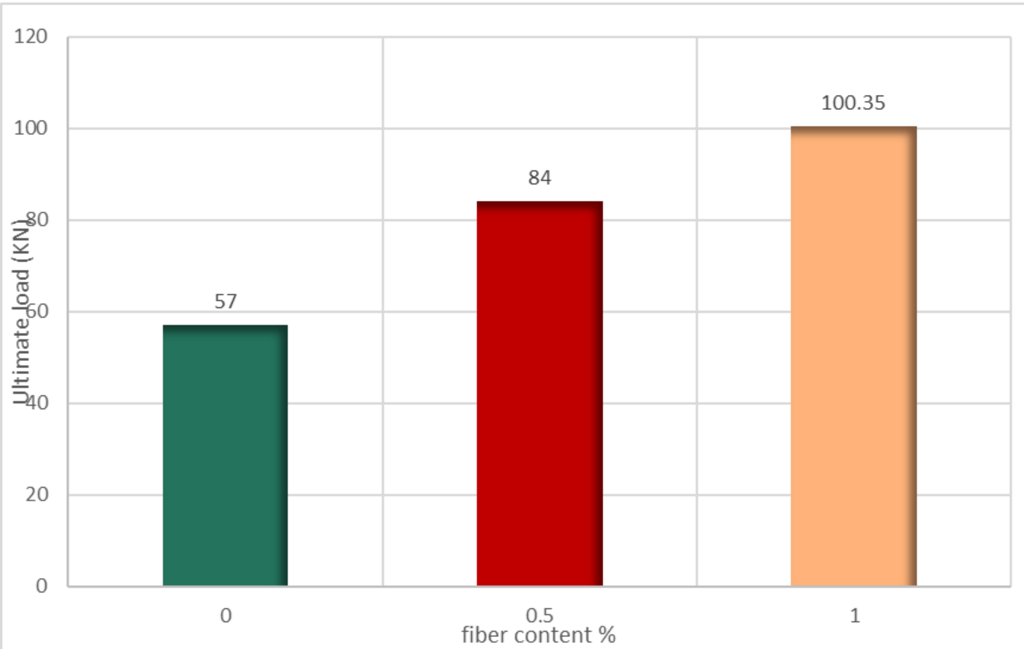

Fig. 11. *Ultimate punching shear load vs Steel fiber content*

7. Load -Deflection response

Fig 12 explains the load- deflection curve for slabs.it is showed the elastic stage without cracks in the load-deflection curves started with linear behaviour, followed by a nonlinear portion of the curve with an elastic cracking behaviour. It is clear that the slabs with steel fiber enhanced the stiffness, ductility, and deformation ability at failure.

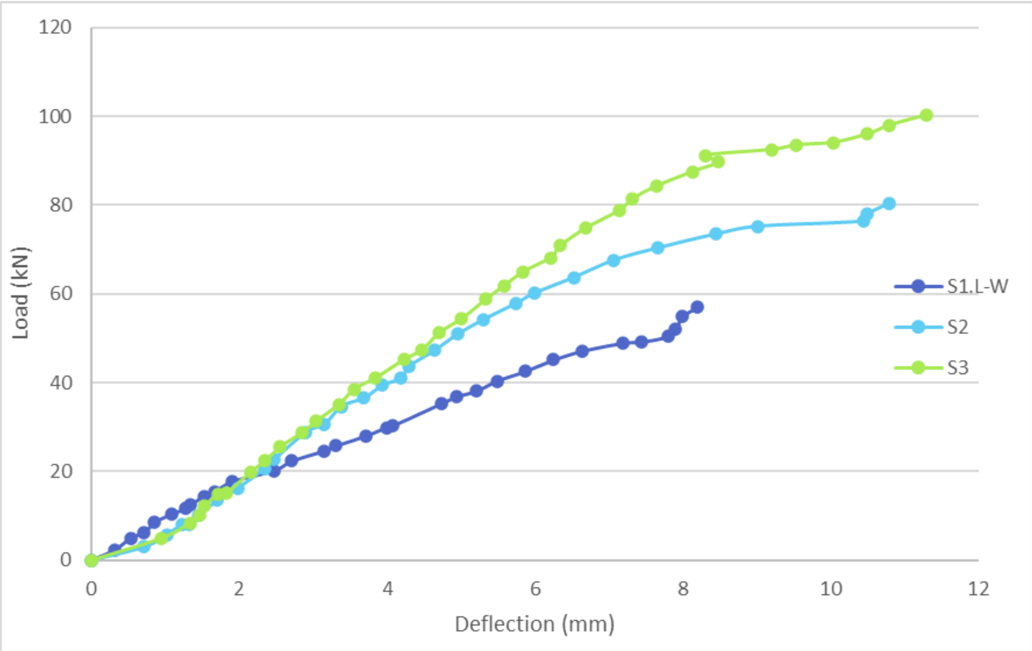

Fig. 12. *Load- deflection curve for slabs*

Figure 13 display the failure mode of slab specimens when the load increased gradually the cracks visually appeared on the tensile area of the slab. and then formed slowly across the whole slab. When the load continued to increase, the cracks spread diagonally from the column toward the slab's corners.

Fig. 13. *Modes of failure and crack patterns*

As the slabs began to fail, a noisy sound was heard and the cut cone-shaped section of the slab around load was pushed downward; this behaviour was reported in [17].

8. Ductility

To ascertain the impact and behaviour of addition crimped steel fiber, the ductility (μ) of the tested slabs has also been computed and listed in Table 14 and figure 14. Equation (1) was utilized to determine the ductility index, in accordance with recommendations found in the literature [18]:

Ductility index =$\delta u/\ \delta is$ Eq. 1

where:

δu is the deflection of the slab at the ultimate load.

$\delta$is the deflection of the slab at the yield load.

Table 14: *ductility of Tested Slabs*

No	Slab symbol	Yield load (kN)	Yield deflection (mm)	Ultimate load (kN)	Ultimate deflection (mm)	Ductility Index
1	**S1-L. W**	50.4	7.8	57	8.2	1.05
2	**S2**	73.48	8.4	80.4	11	1.309
3	**S3**	92.5	9.21	100.3	11.3	1.40

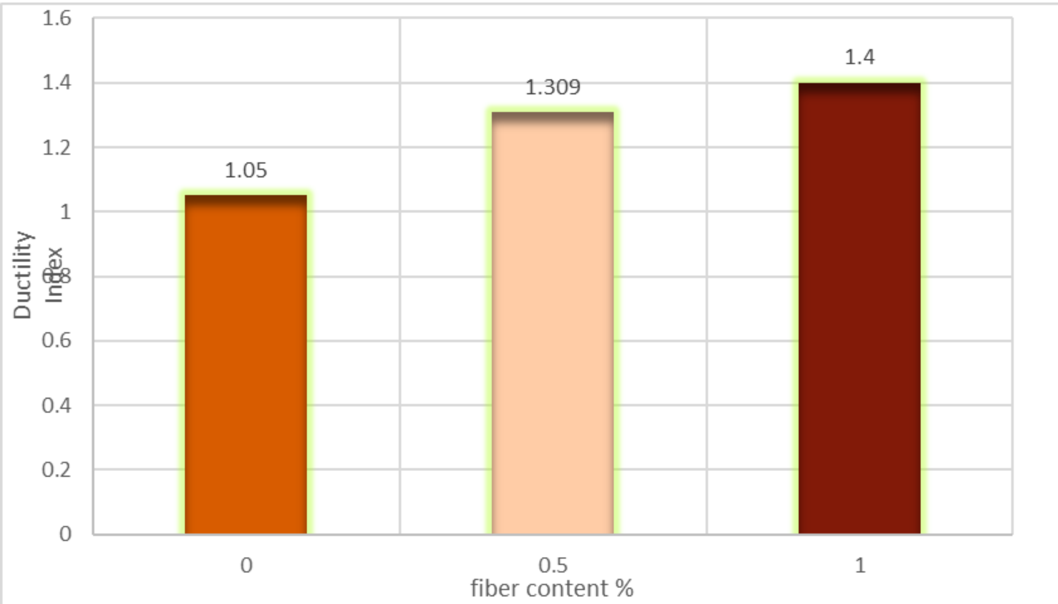

Fig. 14. *ductility of Tested Slabs*

9. Toughness

The toughness of the tested slabs has been calculated and listed in Table 15 and figure 15 to determine the effect LWC replacement ratio and presence of fibers and hybrid fiber on their behaviour. This index has been calculated using Eq. (2), as suggested in the literature [19].

$$Toughnes\ = Area\ under\ \text{“}load\text{–}deflection\ curve\text{"}$$ Eq. 2.

Table 15: *Toughness of the tested slabs*

No	Slab Symbol	Type of Fibers	Vf of fiber (%)	*Toughness*	The increase in *Toughness* (%)
1	**S1-L-W**	No fibre	0	255.14	0
2	**S2**	Steel Fiber (crimped)	0.5	552.13	116.40
3	**S3**	Steel fiber (crimped)	1	789.31	209.36

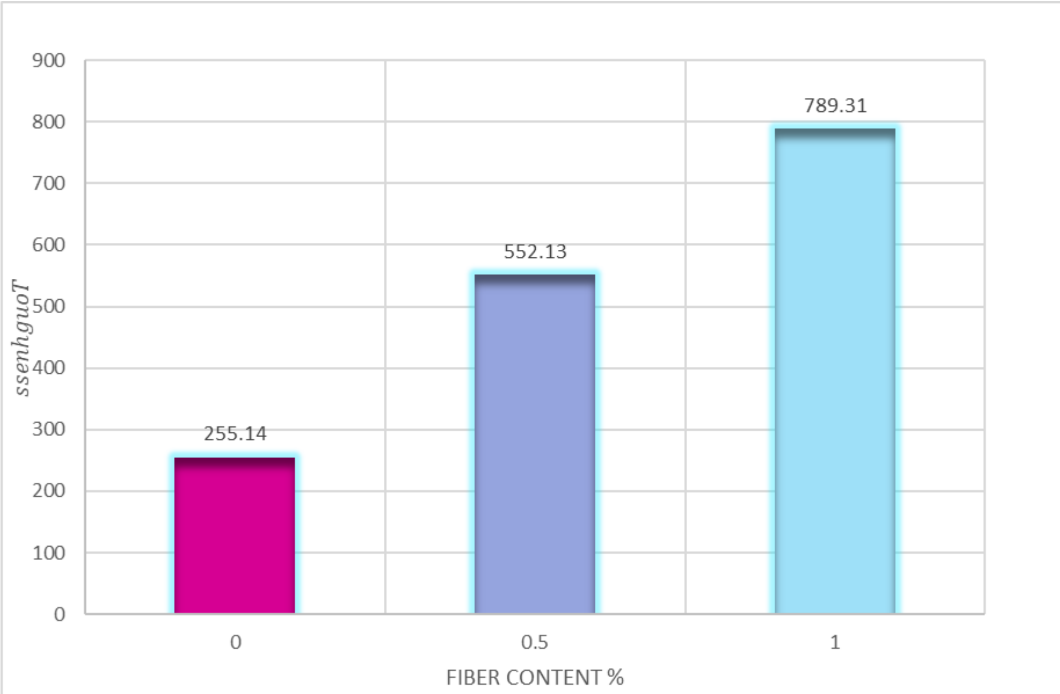

Fig. 15. *Toughness of tested Slab Specimens*

Conclusions

Experimental results showed that as punching shear and cracking increased, so did the amount of crimped steel fiber. It was found that the slab's final load had increased by 47.3 and 76.5, respectively. Compare S2 and S3's volume fractions of 0.5% and 1% of crimped steel fiber used with the control slab (S1-L-W). However, the addition of crimped steel fiber reinforced concrete enhanced the concrete's mechanical qualities, increasing its compressive strength by 20.6 and 29.89 as well as its splitting tensile strength and rapture modules, respectively.

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