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Enhancing Strength and Impact Resistance of Latex Rubberized Concrete through Steel Fiber Incorporation

Siong Kang Lim[1,*], Le Yi Eng[1], Jee Hock Lim[1], Ming Kun Yew[1], Yee Ling Lee[1], Ming Han Lim[1]

[1] Department of Civil Engineering, Lee Kong Chian Faculty of Engineering and Science, Universiti Tunku Abdul Rahman, Bandar Sungai Long, 43000 Kajang, Selangor, Malaysia

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ABSTRACT

Rubberized concrete, which incorporates crumb rubber, offers improved impact resistance, toughness, and ductility compared to regular concrete. However, its strength is typically lower due to weak interfacial transition zones (ITZ) between the crumb rubber and hardened cement paste. This study aims to investigate the potential of steel fiber and Styrene-Butadiene (SBR) Latex in compensating for the strength reduction caused by the inclusion of crumb rubber. Specifically, the research focuses on the effect of incorporating steel fiber into latex rubberized concrete (LRC) on compressive strength, flexural strength, splitting tensile strength, and impact resistance. To determine the optimal mix proportion, trial mixes of LRC and Latex-based rubberized concrete with 15 kg/m3 steel fiber (LRC-15% SF) were tested for their compressive strength, splitting tensile strength, flexural strength, and impact resistance. The selected mix proportion had achieved a minimum of 55 MPa of 28-day characteristic strength. Experimental results indicated that the inclusion of steel fiber led to improved strength properties in LRC. The optimal LRC-15% SF mixture, with a water-to-cement (w/c) ratio of 0.28, outperformed the control mix (w/c ratio of 0.28) by 3.18%, 10.70%, and 17.94% in compressive, splitting tensile, and flexural strengths, respectively, at 56 days. Additionally, the LRC-15% SF exhibited higher impact resistance, showing a 46.27% and 14.71% increase in the 400 mm and 200 mm span length impact tests, respectively, at 56 days. By incorporating steel fiber into latex rubberized concrete, this research demonstrates the potential to enhance the strength properties and impact resistance of the material. These findings contribute to the development of more durable and resilient rubberized concrete formulations, highlighting their potential for various construction applications.

1. Introduction

Over the next three decades, the worldwide production of waste is projected to increase by 70 percent, reaching a total of 3.4 billion tonnes, compared to 2.01 billion tonnes recorded in 2016 [1]. Investigations are currently underway to explore recycling solutions for different types of waste materials. These solutions aim not only to generate new business opportunities and employment but

* *Corresponding author.*
E-mail address: sklim@utar.edu.my

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also to reduce the production of waste materials [2-6]. One of the solid wastes that has been raised up the concern is the tyre rubber. The proper management of waste tyre rubber has emerged as a significant environmental concern [7]. In recent years, the incorporation of crumb rubber into concrete production has garnered significant attention due to its alignment with sustainable development goals. Crumb rubber is typically obtained by reducing used rubber tires into smaller particles [8].

Rubberized concrete (RUC) is a composite material formed by introducing rubber crumbs to replace conventional aggregates in the concrete mixture. This relatively new concrete concept has garnered significant interest among the researchers to study its engineering properties, durability characteristic, interfacial behaviour between the rubber-cement matrix of the rubberized concrete and many more [9-13]. The utilization of crumb rubber in concrete production not only helps maintain ecological equilibrium but also enhances the economic viability of concrete manufacturing. Moreover, the addition of crumb rubber to concrete enhances its ductility and impact resistance [14]. However, it should be noted that previous studies on crumb rubber have indicated a reduction in compressive, splitting, and flexural strengths when incorporated into concrete [15]. This strength reduction is attributed to the formation of a weaker interfacial transition zone (ITZ) between the cement paste and crumb rubber.

As a result, the addition of rubber-modified concrete has been included in the schedule. To address the strength loss associated with incorporating crumb rubber, the use of Styrene-Butadiene (SBR) latex as a binding agent in the production of rubberized concrete has shown potential [16]. Additionally, concrete’s inherent weakness in tension necessitates the inclusion of tensile reinforcement to improve its tensile strength. Steel fiber is a material known for enhancing concrete performance by improving its mechanical properties, including strength and toughness. Compared to conventional reinforced concrete, steel fiber reinforced concrete demonstrates superior strength [17]. Therefore, the incorporation of steel fibers into latex-based rubberized concrete enables the development of sufficient strength, making it an excellent alternative construction material for flexible pavements.

This study aims to select the optimal mix proportion of LRC (latex-based rubberized concrete) and LRC-15% SF (latex-based rubberized concrete with 15% steel fibers) that met the requirements of BS EN 206-1 for concrete used in the construction of railway sleepers, with a minimum 28th day compressive strength of 55 MPa. Subsequently, the effects of incorporating steel fibers into LRC on compressive, flexural, and splitting tensile strengths, as well as impact resistance, were investigated.

2. Methodology

2.1 Materials

This study utilized several materials, which included Ordinary Portland Cement (OPC), coarse and fine aggregates, water, superplasticizer, crumb rubber, Styrene-Butadiene (SBR) latex, silica fume, and steel fiber.

2.1.1 Ordinary portland cement (OPC)

In this study, the specific type of Ordinary Portland Cement (OPC) utilized was Orang Kuat, CEM I OPC, sourced from YTL Cement Sdn Bhd. This OPC variant adheres to the strength class of 52.5 N and complies with the certification of MS EN 197-1 [18]. To ensure its uniformity, the OPC was sieved through a 0.3 mm sieve, eliminating any lumps or impurities. Additionally, it was stored in an air-tight container to prevent exposure to moisture from the surrounding environment.

2.1.2 Coarse and fine aggregates

For this study, locally sourced coarse and fine aggregates were utilized, with a fineness modulus of 7.06 and 2.18, respectively. The fine aggregate underwent sieving through a 4.75 mm sieve, eliminating any coarser particles that remained on the sieve. On the other hand, the coarse aggregate underwent sieving through a series of sieves, including a 20 mm sieve, a 10 mm sieve, and a 4.75 mm sieve. Consequently, particles retained on the 20 mm sieve and those that passed through the 4.75 mm sieve were removed from the aggregate. To ensure consistency in water-to-cement (w/c) ratio when water was added, both the fine and coarse aggregates were subjected to oven-drying at a temperature of (105 ± 5) ºC for 24 hours, effectively removing any initial moisture present in the pores.

2.1.3 Crumb rubber

In this study, crumb rubber was used as a replacement for the fine aggregate, with the substitution being done based on weight. The crumb rubbers employed in this research were natural rubber granules sourced from Yongfeng Rubber, and they adhered to the specifications outlined in ASTM D5644 [19], ASTM D1509 [20], and ASTM D5603 [21]. The crumb rubber particles had a size ranging from 1 to 4 mm and possessed a fineness modulus of 4.62.

2.1.4 Styrene-butadiene (SBR) latex

For this study, a locally manufactured SBR latex was utilized as a bonding agent, specially developed for cement production. SBR latex is a milky white liquid latex that primarily consists of styrene, butadiene, and water. It serves as an effective bonding agent in cement-based materials.

2.1.5 Water and superplasticizer (SP)

In this study, the pure tap water from the municipal water supply was used for both mixing and curing purposes. The water complied with the standards specified in ASTM 1602/C1602M [22]. The water's specific gravity was assumed to be 1.0, and it was maintained at room temperature (27˚C) during the experiments.

A superplasticizer (SP) was employed as a water reducing agent in the concrete mixture. The amount of superplasticizer added depended on the weight of the cement and the quantity of water and latex used in the concrete mix. The superplasticizer used in this study was supplied by the local supplier, BASF.

2.1.6 Silica fume

In this study, silica fume was utilized, which was supplied by a local supplier named Scancem Materials Sdn. Bhd. The main purpose of incorporating silica fume into the concrete mix was to compensate for the potential strength reduction that could occur due to the substitution of fine aggregates with crumb rubber. By adding silica fume, the aim was to enhance the overall strength and performance of the material.

2.1.7 Steel fiber

In this study, the steel fiber (SF) employed was STAHLCON hooked-end steel fiber HE 0.55/35. This type of steel fiber is predominantly manufactured using cold-drawn wire and adheres to the specifications outlined in BS EN 14889-1 [23]. The STAHLCON steel fiber has an elastic modulus of 205,000 MPa. For this research, steel fibers with hooked ends and a quantity of 15 kg in 1m^3 concrete volume was utilized.

2.2 Mix Proportions

The Table 1 shows the mix proportions for various mixes, namely LRC-CTR (latex-based rubberized concrete without steel fibers) and LRC-15% SF (latex-based rubberized concrete with 15% steel fibers). The mix proportions are based on a 1m^3 volume of concrete using absolute method.

Table 1
Mix Proportions

Design Mix	W/C	Unit Weight (kg/m^3)									
		Cement	Aggregate			Crumb Rubber	SBR Latex	Silica Fume	SP	SF
			Fine	20 mm	10 mm					
LRC-CTR 0.32	0.32	667	362	738	369	20	20	40	6.67	0
LRC-CTR 0.30	0.30	667	362	738	369	20	20	40	7.34	0
LRC-CTR	0.28	667	362	738	369	20	20	40	8.00	0
LRC-15 %SF 0.32	0.32	667	362	738	369	20	20	40	7.34	15
LRC-15 %SF 0.30	0.30	667	362	738	369	20	20	40	8.00	15
LRC-15 %SF	0.28	667	362	738	369	20	20	40	8.00	15

Note: The mix proportions are based on 1m^3 concrete volume using absolute method

2.3 Specimens Preparation and Testing Methods

In this study, a total of 108 specimens were prepared for various tests. For the trial mix, 36 cubic specimens were prepared specifically for the compression test. As for the actual mix, 18 cubic specimens were prepared for the compression test, 18 cylindrical specimens were prepared for the splitting tensile test, and 36 prismatic specimens were prepared for the flexural test and repeated drop weight impact test.

2.3.1 Slump test

The slump test, conducted in accordance with ASTM C143/C143M [24], involved placing a 300 mm height slump cone with a 200 mm diameter base on a smooth surface, pouring fresh concrete into the frustum mould in three layers, consolidating the mix with 25 even strokes of a tamping rod in each layer, lifting the frustum mould vertically by approximately 300 mm, and calculating the slump value by subtracting the frustum mould height from the slumped concrete height. The slump test measures the workability or consistency of fresh concrete. It is an important test as it indicates the ease of placing and compacting concrete in the field.

2.3.2 Compacting factor test

The compacting factor test, conducted in accordance with BS EN 12350-4 [25], involved transferring fresh concrete to the upper hopper until it was filled, opening the trapdoor of the upper hopper to allow the concrete to fall into the lower hopper, opening the trapdoor of the lower hopper to let the concrete fall into a standard cylindrical mould, compacting the fresh concrete in the cylinder using a tamping rod until fully compacted, weighing the cylinder with the fully compacted concrete, and repeating the process without compacting the concrete in the cylinder. The compacting factor was determined by calculating the ratio of the weight of the fully compacted concrete to that of the partially compacted concrete.

2.3.3 Compression test

The compression test, in accordance with BS EN 12390-3 [26], was carried out using cubic specimens measuring 150 mm × 150 mm × 150 mm. The test was conducted using a universal compression test machine with a loading rate of 6 kN/s.

2.3.4 Splitting tensile test

The splitting tensile test, in compliance with BS EN 12390-6 [27], was carried out using cylindrical specimens measuring 200 mm in height and 100 mm in diameter. To ensure uniform load distribution along the specimen, packing strips were positioned along the top and bottom of the loading face, centered on the marked lines on the cylinder ends. The test was conducted using a compression test machine with a loading rate of 1.5 kN/s.

2.3.5 Flexural test

The flexural test, in accordance with BS EN 12390-5 [28], was conducted using prism specimens measuring 100 mm × 100 mm × 500 mm. Four vertical lines were drawn on the specimen, spaced at 120 mm and 70 mm from both ends. The test was carried out using a Concrete Flexural Test Machine with a loading rate of 0.15 kN/s.

2.3.6 Repeated drop weight impact test

The repeated drop weight impact test, in compliance with ACI 544 [29], was conducted to evaluate the impact resistance of LRC and LRC-15 % SF. Prism specimens measuring 100 mm × 100 mm × 500 mm were used for the test. In the first impact test, a 2 kg mass was dropped from a height of 200 mm onto the prism concrete specimen with a span length of 400 mm. The half-split prism specimen resulting from the first impact test was then used for the second impact test. In the second test, a 2 kg mass was dropped from a height of 300 mm onto the half-split prism concrete specimen with a span length of 200 mm. The number of drops required to cause the final fracture was recorded. The impact resistance of the concrete was determined by calculating the impact energy using the Eq. (1), where E_{impact} is the impact energy, N is the number of drops to cause the ultimate crack, m is the mass of the drop weight in kg, g is the gravitational acceleration, and h is the height of the drop weight.

$$E_{impact} = Nmgh \quad (1)$$

3. Results

3.1 Trial Mixes Analysis

The trial mixes of cubic specimens for LRC and LRC-15 % SF were prepared and cured for 7 days and 28 days, and the compressive strength results are shown in Figure 1 and Figure 2, respectively, for different water-to-cement (w/c) ratios (0.28, 0.30, 0.32). If the design mix proportion fails to achieve the desired compressive strength of 55 MPa on the 28th day, adjustments such as reducing the w/c ratio may be necessary. For further testing, LRC-CTR with a w/c ratio of 0.28 and a 28th day compressive strength of 56.62 MPa, and LRC-15 % SF with a w/c ratio of 0.28 and a 28th day compressive strength of 60.89 MPa, were selected. These mixes will undergo additional testing to evaluate their compressive, splitting tensile, and flexural strengths, as well as impact resistance.

Figure 1 depicts the compressive strength of trial mixes for LRC-CTR, while Figure 2 shows the compressive strength of trial mixes for LRC-15 % SF.

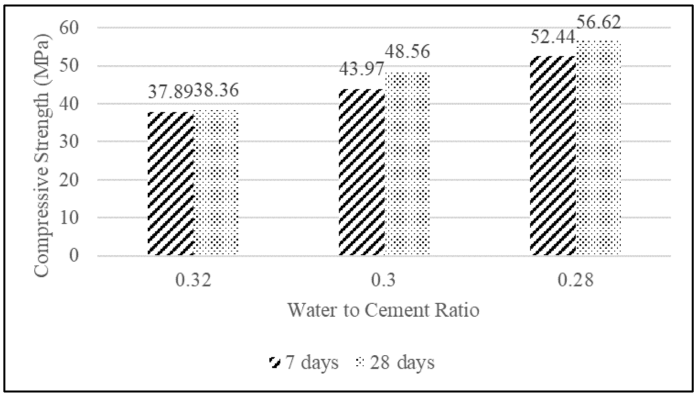


Fig. 1. Compressive strength of trial mixes (LRC-CTR)

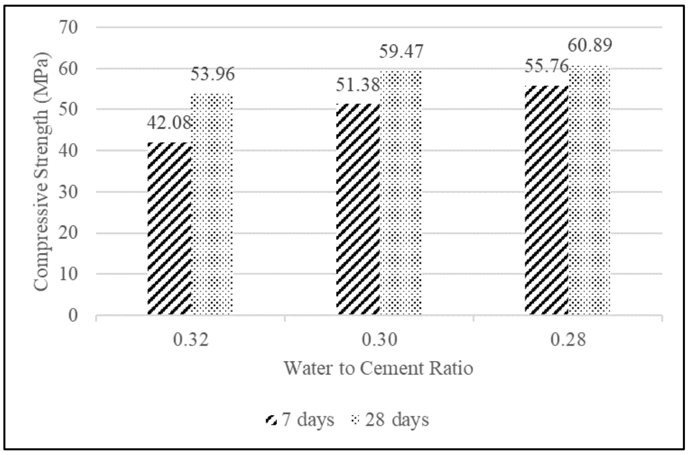


Fig. 1. Compressive strength of trial mixes (LRC-15 % SF)

3.2 Concrete Workability

Figure 3 illustrates that the addition of 15 kg/m^3 of steel fibers resulted in a 7% decrease in slump compared to LRC-CTR, aligning with the findings of Alsaif and Alharbi [30]. The experimental results indicated that the inclusion of steel fibers increased internal friction among the concrete components and led to agglomeration of the fibers, restricting the mobility of aggregates and reducing the workability of fresh concrete. Furthermore, the compacting factor was also diminished with the addition of steel fibers; however, the achieved values still fell within the desired range of 0.80 to 1.00.

Consequently, the fresh concrete exhibited sufficient flowability and was able to fill all spaces within the formwork without experiencing segregation or bleeding.

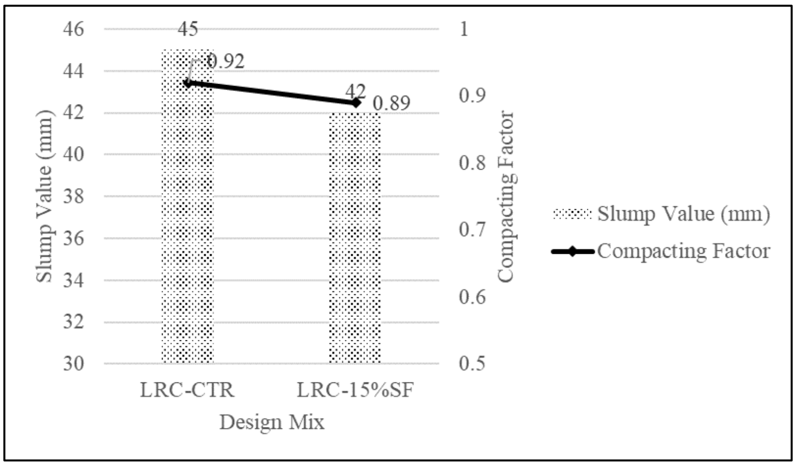


Fig. 2. Workability of LRC-CTR and LRC-15 % SF

3.3 Concrete Density

Based on Figure 4, the addition of steel fibers did not show a significant increase in the fresh and hardened density of the concrete. The results exhibited minimal variations of less than 1%, which aligns with the findings of Chajec and Sadowski [31]. The slight disparity in density between LRC-CTR and LRC-15 % SF can be attributed to the relatively small quantity of the steel fibers, as the weight of the fibers used in this study was less than 1% of the total weight of the concrete.

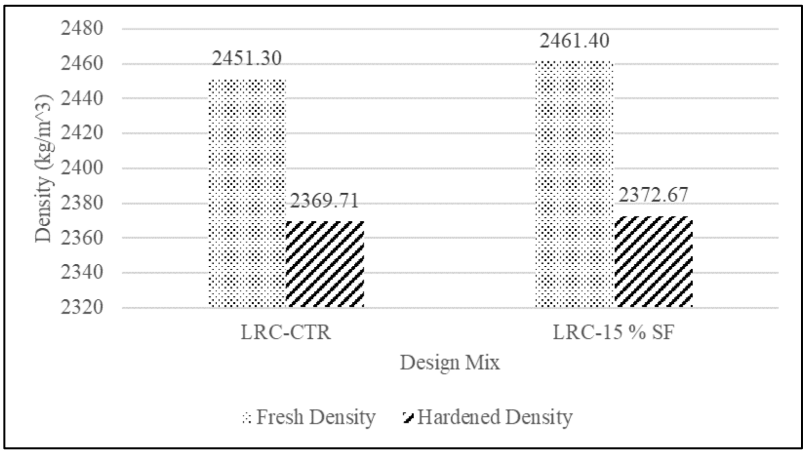


Fig. 3. Density of LRC-CTR and LRC-15 % SF

3.4 Compressive Strength

As depicted in Figure 5, the compressive strength of both LRC-CTR and LRC-15 % SF exhibited an increase with the progression of curing age. Moreover, the addition of steel fibers to LRC resulted in higher compressive strength at all curing ages compared to LRC-CTR. Similar finding was reported by Eisa *et al.,* [15], suggesting that the presence of steel fibers bridged micro-cracks during the early stages of curing, thereby preventing crack formation and leading to increased maximum compressive strength. At 7 days of curing, the compressive strength of LRC-15 % SF was 8.96% higher than that of LRC-CTR. This can be attributed to the early strength gain facilitated by the incorporation of steel fibers, which accelerated the hydration process and enhanced the interlocking of the concrete matrix. Additionally, at 28 days of curing, the compressive strength of LRC-15 % SF was 5.36% higher than that of LRC-CTR, as the continuing hydration process and improved matrix structure contributed to the strength enhancement. Due to the slower rate of strength gain at later ages, the compressive strength of LRC-15 % SF at 56 days was 3.18% higher than that of LRC-CTR. In summary, the inclusion of steel fibers in LRC improved its compressive strength characteristics, particularly during the early stages of curing.

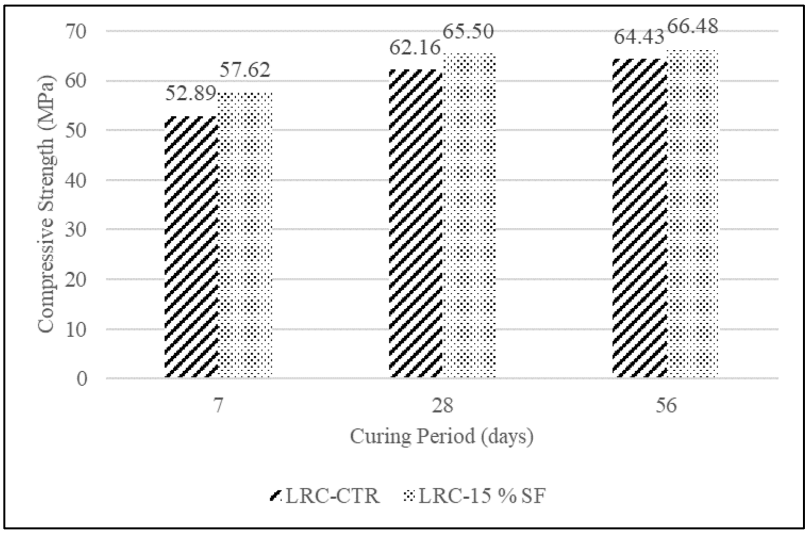


Fig. 5. Compressive Strength of LRC-CTR and LRC-15 % SF

3.5 Splitting Tensile Strength

According to Figure 6, the splitting tensile strength of LRC-15 % SF showed better performance compared to LRC-CTR. The increase in splitting tensile strength for LRC-15 % SF was observed to be 18.80% at 7 days, 16.89% at 28 days, and 10.70% at 56 days, when compared to LRC-CTR. This finding aligns with the results reported by Eisa *et al.*, [15], indicating that the addition of steel fibers to concrete helps bridge microcracks and enhance tensile strength, especially at early stages of curing. The high tensile strength of steel fibers contributes to reinforcing the concrete and preventing crack formation. These results suggest that the incorporation of steel fibers has a positive effect on the splitting tensile strength of LRC, making it more suitable for structural applications.

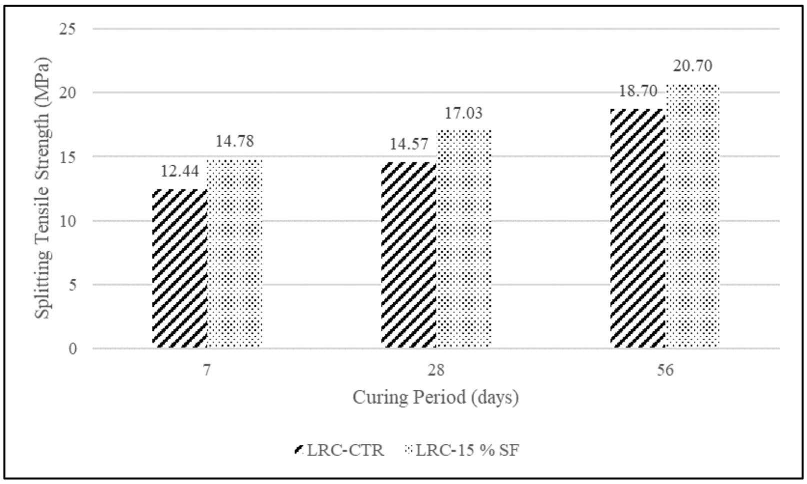


Fig. 6. Splitting Tensile Strength of LRC-CTR and LRC-15 % SF

3.6 Flexural Strength

Based on Figure 7, it can be observed that LRC-15 % SF exhibits higher flexural strength compared to LRC-CTR at all curing times. This can be attributed to the reinforcing effect of steel fibers, which act as bridges between cracks, preventing their propagation and enhancing the load-bearing capacity of the concrete [32]. At 7 days, the flexural strength of LRC-15 % SF is 16.16% higher than that of LRC-CTR. This percentage increases to 24.19% at 28 days and 17.94% at 56 days. The data also indicate that the largest increase in flexural strength occurs at 28 days for both LRC-CTR and LRC-15 % SF. This suggests that the incorporation of steel fibers significantly improves the flexural strength of LRC, particularly after 28 days of curing.

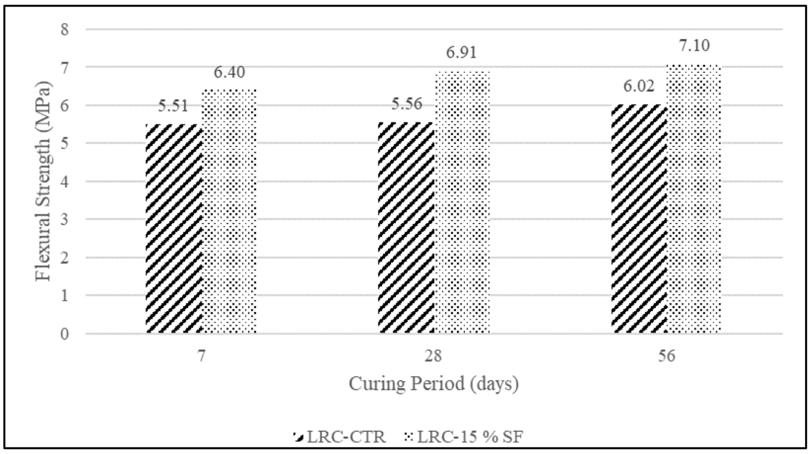


Fig. 7. Flexural Strength of LRC-CTR and LRC-15 % SF

3.7 Impact Resistance

Based on Figure 8, it can be observed that LRC-15 % SF outperforms LRC-CTR in terms of impact resistance in both the 400 mm and 200 mm impact tests. The impact energy absorbed by LRC-15 % SF is significantly higher than LRC-CTR, with a 205.34% increase at 7 days, 82.55% increase at 28 days, and 46.27% increase at 56 days in the 400 mm span length test. Similarly, in the 200 mm span length test, the impact energy absorbed by LRC-15 % SF is 62.97% higher at 7 days, 58.53% higher at 28 days, and 14.71% higher at 56 days. This can be attributed to the presence of steel fibers along the cracks, which enhances the stress transfer mechanism, resulting in increased resistance to crack widening. The incorporation of steel fibers requires a higher amount of impact energy to fracture the bond between the fibers and the concrete, thus improving the overall impact resistance [33].

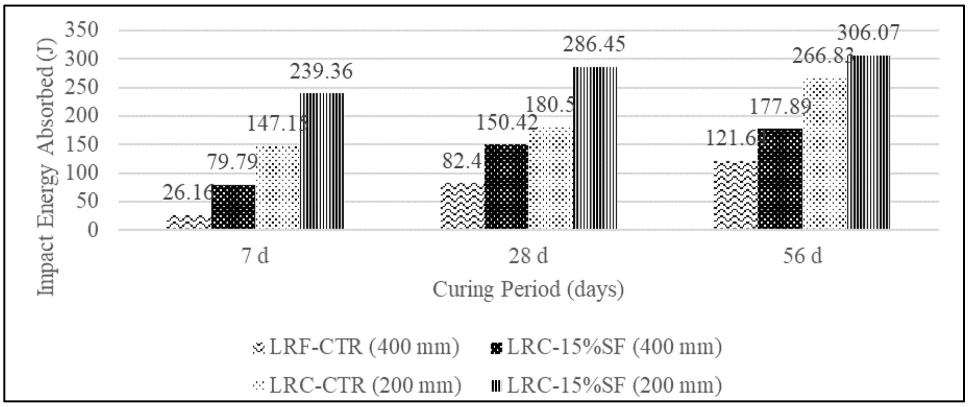
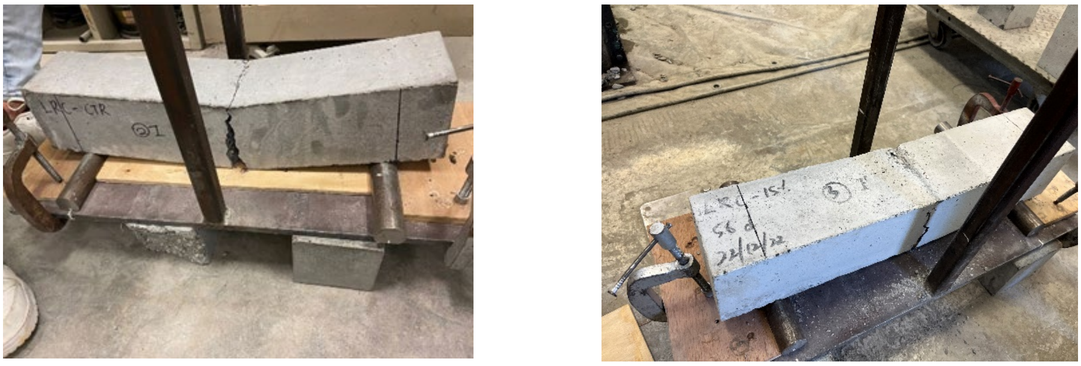


Fig. 8. Impact Resistance of LRC-CTR and LRC-15 % SF

In addition, it is worth noting that the fracture pattern of LRC differed from that of LRC-15 % SF. In the case of LRC, the specimen tends to fragment into two pieces upon impact, as depicted in Figure 9a. On the other hand, LRC-15 % SF exhibits a crack on the specimen surface without significant fragmentation, as shown in Figure 9b. This observation indicates that the incorporation of steel fibers in LRC improves its impact resistance by effectively absorbing energy and reducing the risk of spalling or fragmentation when subjected to impact forces. The steel fibers act as reinforcement, enhancing the overall structural integrity of the concrete and minimizing the extent of damage upon impact.



(a) (b)

Fig. 9. Fracture Pattern of (a) LRC-CTR (b) LRC-15%SF

4. Conclusions

The objectives of this study focused on investigating the effects of incorporating steel fibers into LRC, specifically examining its fresh and hardened properties. LRC and LRC-15 % SF with a w/c ratio of 0.28 were selected for further testing as they met the minimum compressive strength requirement of 55 MPa at 28 days. Based on the experimental findings, the following conclusions can be drawn:

i. The addition of steel fibers to LRC resulted in a reduction in slump value and compacting factor of the fresh concrete. However, there was no significant increase in density observed due to the incorporation of steel fibers.
ii. LRC-15 % SF exhibited higher compressive, splitting tensile and flexural strengths compared to LRC at 7th, 28th, and 56th days of curing. The inclusion of steel fibers as reinforcement in the latex-based rubberized concrete matrix significantly improves its mechanical strength.
iii. LRC-15 % SF demonstrated superior impact resistance compared to LRC. The impact energy absorbed by LRC-15 % SF was higher than LRC in both 400 mm and 200 mm span length impact tests at 7th, 28th, and 56th days. Consequently, the incorporation of steel fibers enhanced the latex based rubberized concrete's ability to absorb energy and reduced the likelihood of spalling or fragmentation upon impact.

Overall, the findings indicate that the addition of steel fibers positively influenced the fresh and hardened properties of LRC, leading to improved mechanical strength and impact resistance. These results highlight the potential of steel fiber reinforcement in enhancing the performance and durability of latex-based rubberized concrete for various applications.

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