Behavior of Micro-Fibre Reinforced Rubberized Concrete Beams under Repeated Loading

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ABSTRACT
Nowadays, an extensive network of highways is being constructed across the globe, resulting in a substantial demand for concrete in road infrastructure. This increasing demand significantly raises construction costs, mainly due to the high consumption of natural aggregates. To address this challenge and promote sustainable construction practices, waste rubber from discarded tyres can be effectively used as a partial replacement for coarse aggregates in concrete. This approach not only helps reduce construction costs but also supports environmental sustainability by recycling non-biodegradable rubber materials. In this context, the present study investigates the cyclic behaviour of rubberized reinforced concrete beams incorporating steel fibres. A total of seven full-scale beams with identical geometry were cast. Among these, one beam served as a control specimen without rubber shreds or steel fibres. The remaining six beams were prepared by partially replacing coarse aggregates with sand-coated rubber shreds at levels of 2.5%, 5%, and 7.5%, in combination with steel fibres at dosages of 0.5% and 1%. All beams were subjected to cyclic loading using a push-pull jack apparatus. The experimental results revealed that beams incorporating steel fibres and sand-coated rubber shreds exhibited enhanced cyclic performance, demonstrated by greater maximum deflection, improved energy absorption capacity, and an increased number of load cycles sustained compared to the control concrete.

Keywords: Stiffness, Energy Absorption, Deflection, micro-reinforcement, Control concrete, rubber shreds.

1. INTRODUCTION

In recent years, concrete technology has undergone a significant transformation, focusing on enhancing performance under diverse environmental conditions. Ongoing research is centered on improving concrete properties through the incorporation of alternative materials for cement, aggregates, and reinforcement. Over time, a wide range of innovative materials has been introduced to serve these purposes. Among them, high-yield strength deformed bars gained popularity; however, they often fell short in delivering the desired level of ductility. While these reinforcements did enhance concrete performance to a certain extent, their limitations highlighted the need for additional strengthening strategies.One effective solution is the inclusion of fibre reinforcement alongside conventional steel reinforcement. Fibre reinforcement can be metallic or synthetic, macro or micro, and may be used either as single-type (mono) or combined types (hybrid). Fibre-reinforced concrete exhibits significant improvements in key engineering properties such as fatigue resistance, impact strength, ductility, and crack resistance. Simultaneously, the accumulation of waste rubber has emerged as a pressing global environmental issue. Disposing of used rubber—particularly tires—through landfilling poses ecological risks, making recycling and reuse a necessity. Research has identified waste rubber as a promising material for civil engineering applications. When appropriately processed, rubber can be utilized as a partial replacement for mineral aggregates in concrete. However, replacing aggregates with crumb rubber may lead to a reduction in mechanical properties due to the weak bonding at the rubber–cement interface.To address this issue, several surface treatment methods have been explored to improve the interfacial transition zone between rubber particles and the cement matrix. These include alkali etching, surface coatings, treatment with NaOH solution, coupling agents, thin cement paste coatings, styrene-butadiene rubber, and natural sulfur varnishes. Some of these treatments have proven effective in enhancing the mechanical performance of rubberized concrete. Furthermore, incorporating steel fibres into concrete improves its toughness, ductility, and resistance to impact and fatigue, especially under post-cracking conditions. This is particularly beneficial for structures in seismic zones, where ductility is crucial for energy dissipation and structural integrity during earthquakes. Micro-reinforcement, in particular, plays a vital role in enhancing the post-crack resistance, toughness, and fatigue performance of concrete. The integration of steel fibres converts brittle concrete into a more ductile material, making it suitable for demanding structural applications. In this study, the cyclic performance of rubberized concrete beams incorporating steel fibres is examined through experimental modeling. The research focuses on evaluating the cyclic behavior of full-scale reinforced concrete beams containing both longitudinal and transverse steel reinforcement. Seven full-scale specimens were tested under four-point cyclic loading, with varying contents of pre-treated rubber shreds (2.5%, 5%, and 7.5%) and steel fibre volume fractions (0.5% and 1%). Key parameters such as the number of cycles sustained, maximum deflection, stiffness under loading, and total energy absorption were analyzed to understand the influence of steel fibres on the cyclic performance of rubberized concrete beams.

2. EXPERIMENTALPROGRAM

2.1*Materials and specimens*

Portland cement was used in the concrete mix. Rubber shreds of 20 mm size with a specific gravity of 1.24, prepared from discarded conveyor belts collected from a thermal power plant, were used as partial replacements for coarse aggregate. The specimens were prepared with varying dosages of pretreated rubber shreds: 2.5%, 5%, and 7.5%.Figure 1 shows the waste conveyor belt rubber used in the study. Figure 2 illustrates the application of resin to the rubber shreds for sand coating. Figure 3 displays the finished sand-coated rubber shreds. Figure 4 presents the steel fibres used in the mix, which have a uniform diameter and were added as micro-reinforcement in varying dosages of 0.5% and 1.0%.

Fig.1 Rubber Shreds

Fig.3 Sand Coated Rubber Shreds

Fig.2 Resin Bath

Fig.5 Steel Fibre

Seven reinforced beams of concrete mix with sand coated rubber shreds (2.5%,5% &7.5%)steel fibers (0.5% and 1%) were prepared in the laboratory of Annamalai university . One sample was prepared without steel fibers and the rest of the samples were rubberized concrete beam with steel fibres. The shape of the fibers is hooked and the size of the fibers is 60 and 0.8 mm in length and diameter, respectively.

The dimensions of the specimens are 3000mm and 150x250 mm in length and cross section, respectively. The top and bottom longitudinal and transverse bars are 2Φ10 and Φ 2@12 mm, respectively. The corresponding yield strength is 4000 and 3000 kg/cm2, respectively. Figure 5 Alt text: shows the details of the rectangular beam with longitudinal and transverse reinforcement. The length of the cover to concrete is 25 mm.

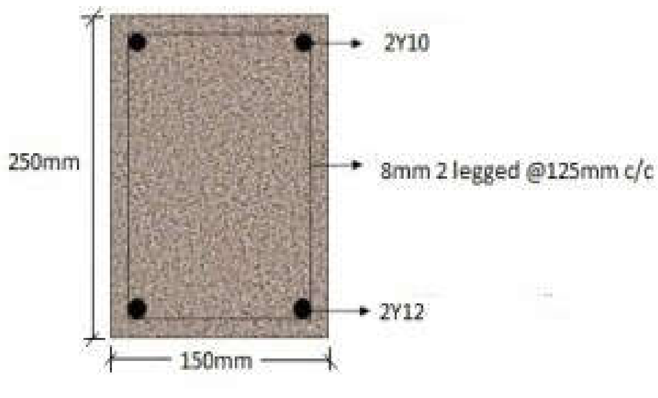


Fig.5 Reinforcement Details

2.2 Setup of Experimental Models

The cast specimens were subjected to cycling loading using push-pull jack in a loading frame of 500 kN capacity. The beams were mounted on rollers and hinges in such a way that the test span was 2.8m. Four - point bending was accomplished through the use of a distribution girder. The displacements were measured at desired locations using displacement gauges with 0.01mm precision. Crack width was measured using a crack detection microscope of 0.02mm precision. Crack growth was monitored throughout the loading history. In Figure .6 Alt text: shows the beam setup, which is used to facilitate load application and displacement measurement at pre-selected locations.

Fig.6 Loading Arrangement and Instrumentation

3. RESULTS AND DISCUSSION

3.1 Effectof Pretreated Supplementary Aggregates and Micro-Reinforcement on Load Capacity, Deformations and Energy Absorption

The influence of cyclic loading on the behaviour of rubberized concrete beams with micro - reinforcement is discussed in this section. All the test specimens were subjected to cyclic loading until failure.

Table.1 Cyclic Test Results of Rubberized Concrete Beam (CR11, CR12)

SI.No	Identification of beams	Number of Cycles	Deflection in (mm)	Total Energy Absorption in kN.mm
1	CC	6	15.0	289.17
2	CR11	11	22.5	1450.14
3	CR12	13	27.2	2034.83

The number of cycles sustained, maximum deflection, and energy absorption for fibre-reinforced rubberized concrete beams are presented in Table 1. The CR12 beams exhibited notable improvements compared to both the control concrete (CC) and CR11 beams, with increases of 11.66% in the number of cycles, 81.33% in maximum deflection, and 603.37% in energy absorption. Figure 7(a)–(c) illustrates these enhancements as percentage increases for the CR12 beams.The observed improvement in the number of cycles sustained by CR12 beams can be attributed to the increased micro-reinforcement content (1%), which significantly enhances the fibre–matrix interfacial bond. The flexural rigidity (EI) of CR12 was higher than that of CC and CR11 beams, due to the effective tying action of the micro-reinforcement that helps regulate micro-crack development. Additionally, the introduction of micro-reinforcement generated a beneficial synergistic interaction with the aggregates. The superior energy absorption capacity of rubber shreds, compared to conventional aggregates, also contributed to the enhanced performance

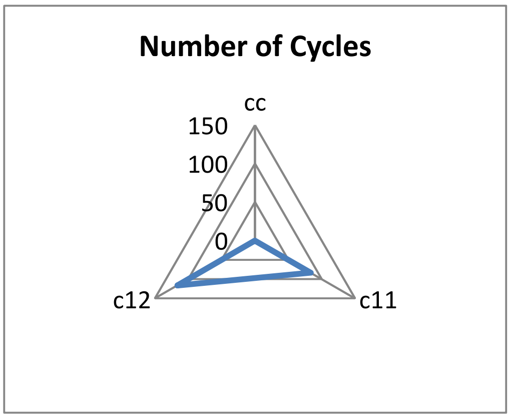


Fig. 7(a)

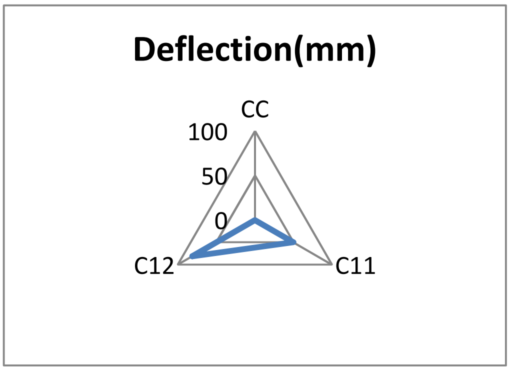


Fig. 7(b)

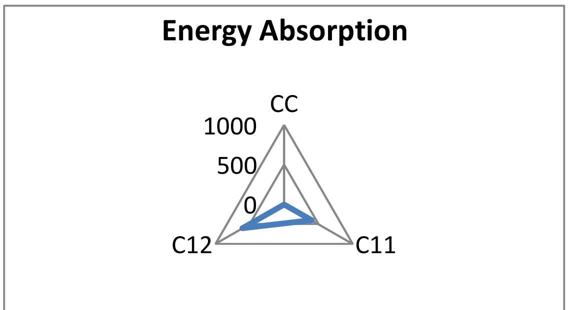


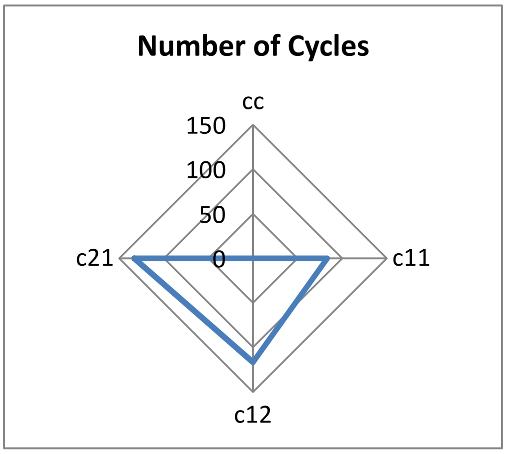
Fig.(c)

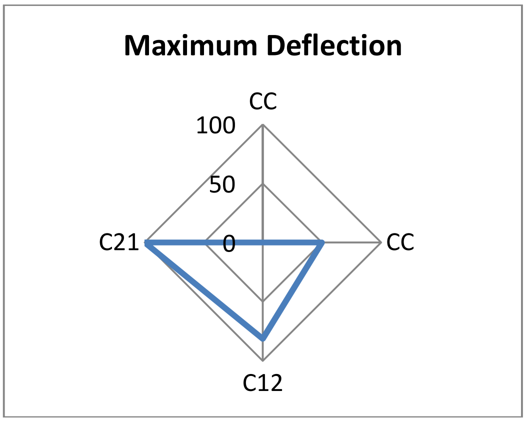
Fig.7 (a)-(c) Response of Sand coated Aggregates and Micro-Reinforcement on Number of Cycles sustained, Maximum Deflection and Energy Absorption(CR12)

Table. 2 Cyclic Test Results of Micro-reinforced Rubberized Concrete Beam (CR21)

SI.No	Identification of beams	Number of Cycles	Deflection in (mm)	Total Energy Absorption in kN.mm
1	CC	6	15.0	289.17
2	CR11	11	22.5	1450.14
3	CR12	13	27.2	2034.83
4.	CR21	14	30	3032.45

The number of cycle's sustained, maximum deflection and energy absorption for rubberized concrete beam with fibre reinforcement is presented in Table.2. The beams CR21 exhibit an increase in number of cycle (13.33%), maximum deflection (100%) and energy absorption (948.67%) when compared to CC ,CR11 and CR12 beam. Figure.8 (a)-(c) Alt text: shows the percent increase in the number of cycle's sustained, maximum deflection and energy absorption of CR21 beam. For CR21 beam, the improvement in the number of cycles can be attributed to the following: The increase in quantity of sand coated rubber shreds (5%) and micro-reinforcement (0.5%) is significantly strengthened the fiber-matrix interfacial bond. Flexural rigidity (EI) of CR21 is higher whereas compared to remaining three beams (CC,CR11&CR12) as a result of the tying action of micro-reinforcement, which regulates the micro-cracking of concrete. The inclusion of micro-reinforcement also had positive synergistic effects with aggregates. Compared to conventional aggregates, rubber shreds have a higher capacity to absorb energy.





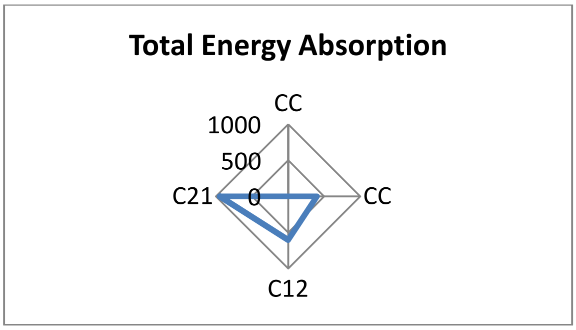
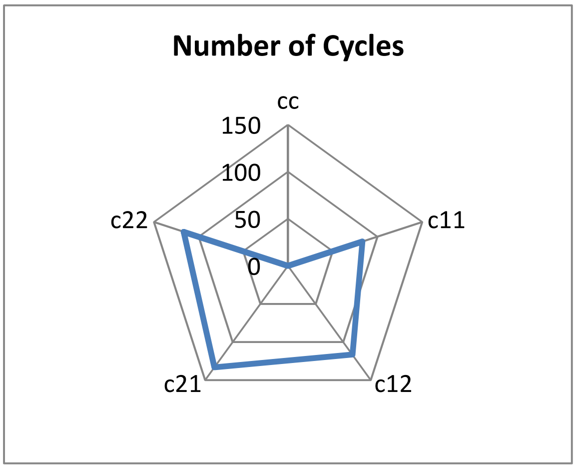


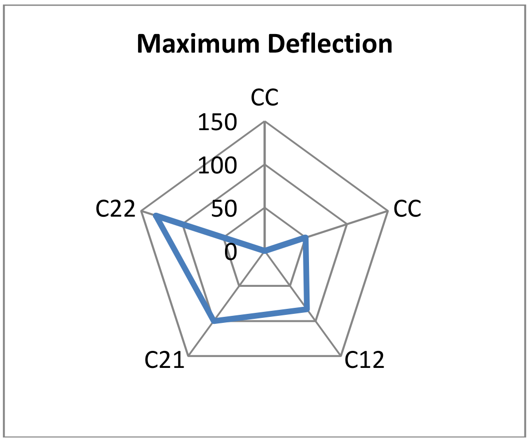
Fig.8 (a)-(c) Response of Pretreated Supplementary Aggregates and Micro-Reinforcement on Number of Cycles sustained, Maximum deflection and Energy Absorption (CR21)

Table. 3 Cyclic Test Results of Micro-reinforced Rubberized Concrete Beam (CR22)

SI.No	Identification of beams	Number of Cycles	Deflection in (mm)	Total Energy Absorption in kN.mm
1	CC	6	15.0	289.17
2	CR11	11	22.5	1450.14
3	CR12	13	27.2	2034.83
4.	CR21	14	30	3032.45
5.	CR22	16	34.8	3864.06

The number of cycles sustained, maximum deflection, and energy absorption for fibre-reinforced rubberized concrete beams are presented in Table 3. The CR21 beam demonstrated significant improvements compared to the CC, CR11, and CR12 beams, with increases of 13.33% in the number of cycles, 100% in maximum deflection, and 948.67% in energy absorption. Figure 8(a)–(c) shows the percentage increases in these parameters for the CR21 beam.The enhanced performance of the CR21 beam can be attributed to the combined effect of 5% sand-coated rubber shreds and 0.5% micro-reinforcement, which substantially improved the fibre–matrix interfacial bond. The flexural rigidity (EI) of CR21 was higher than that of the other beams (CC, CR11, and CR12), primarily due to the tying action of the micro-reinforcement, which effectively regulated micro-crack propagation. Furthermore, the inclusion of micro-reinforcement exhibited beneficial synergistic interactions with the aggregates. Rubber shreds, when compared to conventional aggregates, also contributed significantly to energy absorption due to their superior capacity for dissipating energy





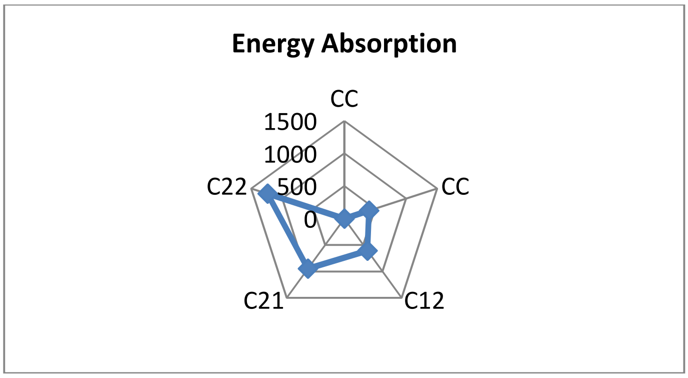


Fig.9 (a)-(c) Response of Pretreated Supplementary Aggregates and Micro-Reinforcement on Number of Cycles sustained, Maximum deflection and Energy Absorption(CR22)

Table.4 Cyclic Test Results of Micro-reinforced Rubberized Concrete Beam (C31)

SI.No	Identification of beams	Number of Cycles	Deflection in (mm)	Total Energy Absorption in kN.mm
1	CC	6	15.0	289.17
2	CR11	11	22.5	1450.14
3	CR12	13	27.2	2034.83
4.	CR21	14	30	3032.45
5.	CR22	16	34.8	3864.06
6.	CR31	18	35.6	4749.3

The number of cycles sustained, maximum deflection, and energy absorption for fibre-reinforced rubberized concrete beams are presented in Table 4. The CR31 beam exhibited substantial improvements compared to CC, CR11, CR12, CR21, and CR22 beams, with increases of 146.3% in the number of cycles, 137.33% in maximum deflection, and 1542.36% in energy absorption. Figure 10(a)–(c) illustrates these percentage increases for the CR31 beam.The remarkable performance of the CR31 beam can be attributed to the combined addition of 0.5% micro-reinforcement and 7.5% sand-coated rubber shreds, which significantly enhanced the fibre–matrix interfacial bond. The flexural rigidity (EI) and sectional modulus of CR31 were higher than those of the other beams due to the increased fibre content. This improvement is primarily due to the tying action of the micro-reinforcement, which effectively controls micro-crack propagation. Moreover, the inclusion of micro-reinforcement fostered favourable synergistic interactions with the aggregates. Rubber shreds, compared to conventional aggregates, demonstrated a superior ability to absorb energy, further contributing to the beam's enhanced performance.

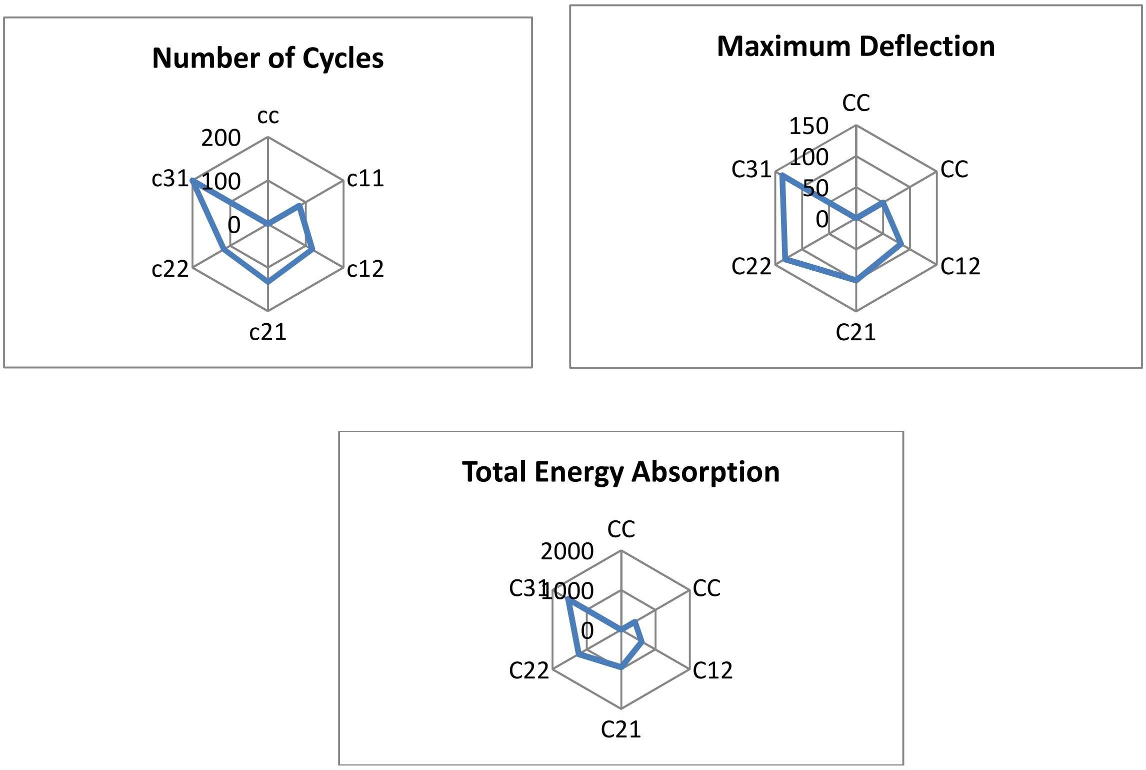


Fig. 10(a)-(c) Response of Pretreated Supplementary Aggregates and Micro-Reinforcement on Number of cycles sustained, Maximum deflection and Energy Absorption(CR31)

Table.5 Cyclic Test Results of Micro-reinforced Rubberized Concrete Beam (CR32)

SI.No	Identification of beams	Number of Cycles	Deflection in (mm)	Total Energy Absorption in kN.mm
1	CC	6	15.0	289.17
2	CR11	11	22.5	1450.14
3	CR12	13	27.2	2034.83
4.	CR21	14	30	3032.45
5.	CR22	16	34.8	3864.06

6.	CR31	18	35.6	4749.3
7.	CR32	19	40.0	5293.509

The cyclic test results for the micro-reinforced rubberized concrete beam CR32 are presented in Table 5. Compared to the other beams (CC, CR11, CR12, CR21, CR22, and CR31), the CR32 beam demonstrated the most significant enhancements, with increases of 166.67% in the number of cycles sustained, 154.66% in maximum deflection, and 1794.38% in energy absorption. Figure 11(a)–(c) presents the percentage improvements in these parameters for the CR32 beam.These outstanding improvements can be attributed to the combined effect of 1% micro-reinforcement and 7.5% sand-coated rubber shreds**,** which greatly enhanced the fibre–matrix interfacial bond. The CR32 beam also showed the highest flexural rigidity (EI) and sectional modulus among all tested beams, owing to the increased content of micro-reinforcement. This reinforcement effectively restricted the propagation of micro-cracks through a tying mechanism. In addition, the interaction between the micro-reinforcement and the aggregates generated a beneficial synergistic effect, improving the structural integrity of the beam. The superior energy absorption capacity of rubber shreds, when compared to conventional aggregates, further contributed to the improved cyclic performance of the CR32 beam.

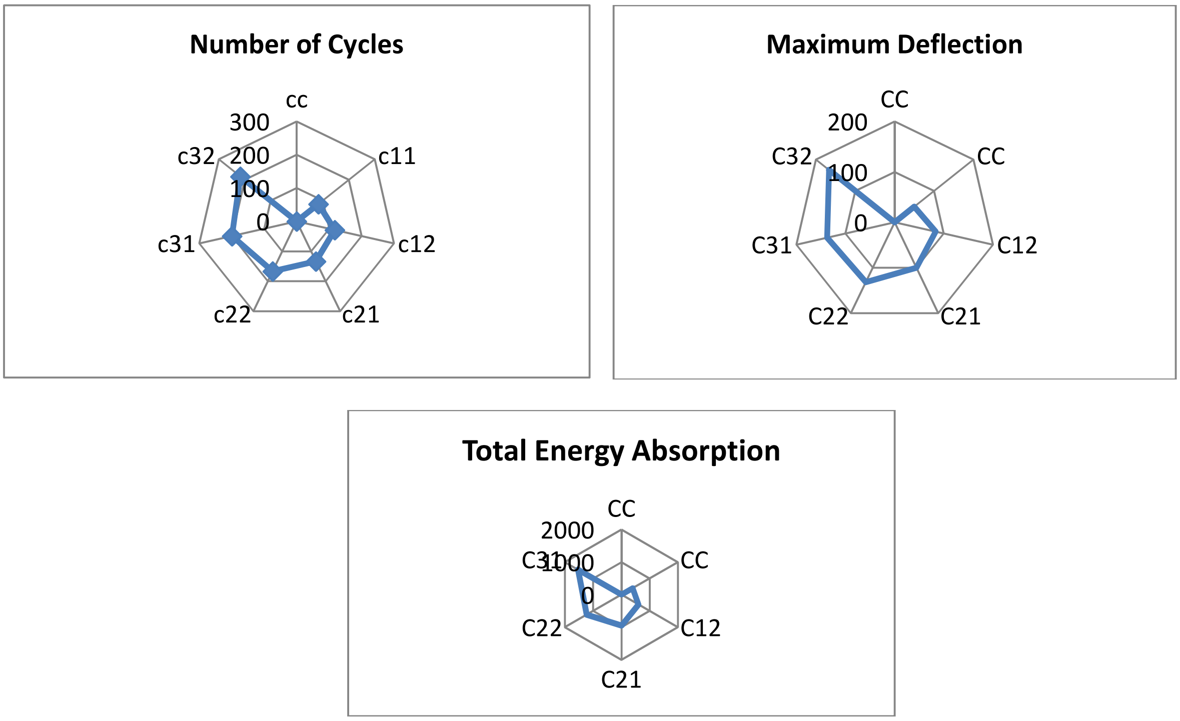


Fig. 11(a)-(c) Response of Pretreated Supplementary Aggregates and Micro-Reinforcement on Number of cycles sustained, Maximum deflection and Energy Absorption (CR32)

3.2 Impact of Sand coated Rubber Aggregates and Micro-Reinforcement on Failure Mode

Figures 12 to 18 Alt Text: illustrate the way the beam specimens failed. The test beams were found to have failed as a result of internal rebar fracture. When cyclic loads are applied, degradation grows up because of both the loss of stiffness and an increased amount of deflection as the number of load cycles increases. The local slip of the reinforcing bars at the crack locations and the pushing of fragments in the flexural cracks that happened during cycling are responsible for the spike in deflection in relation to the increase in the number of cycles. Fragments prevents the cracks from healing entirely contributing to the strain on the steel. The effective moment of area diminished when cracks form and develop. The deflection escalates as a result. Both the control and steel fibre reinforced rubberised concrete beams observe an increase in tensile stresses in the reinforcing steel when fatigue loading is utilised. As fatigue cracks multiply, the strains in tension steel grow drastically. The matrix's already present tiny cracks unite to form a single isolated macro crack under repeated loading, resulting from which the crack proceeds to extend along the vulnerable line (aggregate-paste bond). It seems that the deflection develops quickly before the reinforcement fractures suggests that the impending failure can be noticed by monitoring the deflections. Throughout the fatigue failure loading, the RC beams with steel fibres display controlled damaged accumulation rates (increase in deflection) and suffer less bond degradation. Similar to the deflection increase, the rate of stiffness deterioration under fatigue loading climbs dramatically during the first few cycles and near the ending of fatigue testing, while increasing steadily in the subsequent cycles. Additionally, the initial few cycles are when the maximum crack width originates, and as the number of load cycles increases, the maximum crack width and depth tend to increase relatively slowly.

4. CONCLUSIONS

The experimental investigation revealed that reinforced concrete beams incorporating 7.5% rubber shreds and 1% steel fibres exhibited enhanced performance under cyclic loading, particularly in terms of the number of cycles sustained, maximum deflection, and energy absorption capacity. The primary failure mode observed in all specimens was the rupture of reinforcement bars, indicating that the concrete matrix maintained its integrity throughout the loading process. Additionally, the use of resin-based sand coating on rubber shreds proved effective in improving the interfacial transition zone between the rubber particles and the cement matrix, thereby contributing to the improved mechanical behavior of the rubberized concrete.

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