

# Flexural Behavior of Rubberized Ferrocement Beams Reinforced by GFRP and Steel Wire Rope: A Comprehensive Review



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**ABSTRACT:** Ferrocement is widely recognized for its lightweight characteristics and high tensile efficiency; however, it faces limitations related to durability and ductility, particularly under aggressive environmental and loading conditions. This study presents a comprehensive review of the flexural behavior of rubberized ferrocement beams reinforced with hybrid Glass Fiber Reinforced Polymer (GFRP) and Steel Wire Rope (SWR), aiming to address these challenges. The methodology is based on a systematic evaluation and synthesis of recent experimental, analytical, and finite element studies, focusing on material properties, bond behavior, reinforcement mechanisms, and structural performance of rubberized and hybrid-reinforced systems. The results indicate that the incorporation of crumb rubber significantly enhances ductility, energy absorption, and crack control, although it leads to moderate reductions in compressive and flexural strength. GFRP reinforcement provides high tensile strength and corrosion resistance but exhibits relatively brittle behavior, whereas SWR contributes superior ductility and post-cracking performance. Hybrid GFRP–SWR systems demonstrate improved overall behavior by combining strength, durability, and deformation capacity. Furthermore, the findings highlight that surface treatment, bond optimization, and proper reinforcement detailing are critical factors governing structural efficiency and serviceability. Based on the reviewed literature, it is recommended that future research focus on large-scale structural validation, long-term durability under environmental and cyclic loading, advanced bond modeling at the material interface, and comprehensive life-cycle assessment. These directions are essential to support the practical implementation and code development of rubberized ferrocement systems with hybrid reinforcement.

**KEYWORDS:** Rubberized ferrocement; GFRP reinforcement; Steel wire rope; Hybrid composite beams; Flexural behavior.

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## I. INTRODUCTION

Ferrocement, a thin, highly reinforced cementitious composite, consists of a rich mortar matrix and closely spaced layers of fine wire mesh or skeletal reinforcement, which provides enhanced tensile behavior and crack control (Kaushik et al., 2025). Originating from mid-20th century innovations in thin-shell and prefabricated construction, ferrocement has been widely recognized for its excellent moldability, high tensile strength per unit thickness, and superior crack resistance compared to conventional reinforced concrete of similar thickness (Gopal and Shobarajkumar, 2024). Its low self-weight, ease of manual fabrication, and favorable toughness have enabled its application in a wide range of structures, including water tanks, boat hulls, retrofitting overlays, and architectural shells (Shinde et al., 2022). Recent studies and technical reviews have reaffirmed the continued relevance of ferrocement in lightweight and repair applications, while emphasizing the need to modernize material compositions and reinforcement strategies to meet current durability and sustainability requirements.

Despite these advantages, conventional ferrocement faces two major engineering challenges that have motivated recent research developments. First, the use of thin steel wire meshes combined with limited concrete cover increases susceptibility to corrosion in aggressive environments such as marine conditions, wastewater exposure, and deicing salts, thereby compromising long-term durability and increasing maintenance costs (Katiyar et al., 2024). Second, although ferrocement exhibits distributed cracking behavior, certain configurations may still demonstrate relatively brittle post-peak responses due to limited ductility under extreme or cyclic loading conditions (Ma et al., 2021; Zivkovic et al., 2024). These limitations have prompted the exploration of alternative reinforcement systems and matrix modifications aimed at simultaneously improving durability, serviceability, and energy absorption capacity.

One promising approach to enhancing matrix performance is the partial replacement of fine aggregates with recycled crumb rubber. The inclusion of rubber particles in mortar and concrete mixtures has been shown to reduce density and initial stiffness while significantly improving toughness, impact resistance, vibration damping, and post-

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cracking deformation capacity (Pham et al., 2018; Huang et al., 2020). Several studies have reported that moderate rubber contents, typically in the range of 5–15% by volume or mass, can enhance ductility and energy absorption, although this is often accompanied by reductions in compressive and flexural strength (Strukar et al., 2017; He et al., 2023; Saad et al., 2025). Nevertheless, strength reductions can be mitigated through appropriate pre-treatment techniques, such as mechanical processing or chemical treatment, and through optimized mix design incorporating supplementary cementitious materials, fibers, or polymer modifiers, which improve the bond between rubber particles and the cementitious matrix (Gravina, 2019; Qureshi et al., 2024). Consequently, rubberized matrices offer a sustainable solution by recycling waste tires while tailoring mechanical performance for applications where toughness and resilience are prioritized over stiffness.

From a reinforcement perspective, Glass Fiber Reinforced Polymer (GFRP) bars and steel wire rope (SWR) provide complementary solutions to address corrosion resistance and ductility requirements, respectively (Zeng et al., 2021). GFRP bars are characterized by a high strength-to-weight ratio and excellent resistance to corrosion, making them suitable for harsh environments and long-term applications (Dantino et al., 2018). However, their relatively low modulus of elasticity and linear-elastic brittle failure behavior require careful consideration of serviceability and ductility, particularly in terms of deflection and crack control (El-Hassan and El-Maaddawy, 2019). Recent studies have highlighted the importance of surface treatments, such as sand-coating and helical grooving, as well as adequate development length, to ensure reliable bond and anchorage performance (Hussein, 2023; Polanco, 2024). In contrast, steel wire ropes exhibit high tensile strength, excellent ductility, and superior post-cracking energy dissipation due to the progressive yielding of individual strands, which enhances deformation capacity when properly anchored (Qin, 2025). The combination of GFRP and SWR in hybrid reinforcement systems aims to integrate the corrosion resistance and lightweight characteristics of FRP with the ductility and energy absorption capacity of steel wire ropes, resulting in improved structural performance and balanced behavior (Ribeiro et al., 2024). Experimental and field studies have demonstrated promising outcomes for both GFRP strengthening techniques and bonded wire rope systems (Hussein, 2023; Haddad and Obeidat, 2024).

Despite the growing body of literature on rubberized matrices and hybrid reinforcement systems, several critical research gaps remain (Mirdarsoltany et al., 2022). The interaction between rubber-modified matrices and non-traditional reinforcements, including GFRP bars with different surface treatments and multi-strand steel wire ropes, is not yet fully understood in terms of bond-slip behavior, development length, and long-term durability under environmental and cyclic loading. Furthermore, most existing studies are limited to small- and medium-scale laboratory experiments, with limited validation at the structural scale, such as full-size bridge elements or large-

span systems (Saber et al., 2025). In addition, life-cycle assessment and reliability-based analyses that integrate mechanical performance with environmental impact and maintenance costs are still scarce. Current design codes also remain conservative or incomplete regarding rubberized and hybrid ferrocement systems, limiting their widespread adoption. Finally, there is a need to balance serviceability requirements, particularly deflection and crack-width control, with the intended improvements in ductility and energy absorption, especially in GFRP-reinforced systems where modulus mismatch can lead to increased deformations.

Accordingly, this review aims to synthesize recent experimental, analytical, and sustainability-oriented research on rubberized ferrocement beams reinforced with GFRP and steel wire rope. The objectives are to (1) critically evaluate the flexural performance, including strength, stiffness, failure modes, and bond behavior; (2) assess the effectiveness and limitations of GFRP and SWR, both individually and in hybrid systems; (3) identify key research gaps related to durability, standardization, and life-cycle performance; and (4) provide recommendations for future research and the development of performance-based design approaches. Particular emphasis is placed on studies published within the past decade to ensure relevance to current materials, technologies, and sustainability considerations.

## II. FUNDAMENTALS AND MATERIALS

This section presents the fundamental materials and reinforcement systems used in rubberized ferrocement composites, including ferrocement, rubberized mortar, GFRP bars, steel wire rope (SWR), and their hybrid combinations. It summarizes their key mechanical properties, advantages, and limitations while highlighting their roles in enhancing structural performance, durability, and sustainability. Understanding these constituent materials provides the foundation for the subsequent discussion of hybrid rubberized ferrocement behavior.

### A. Ferrocement Composites

Ferrocement was a cementitious composite that was thin, highly reinforced and consisted of a rich matrix of mortar and a series of layers of closely spaced wire mesh or skeletal reinforcement (Ramalingam et al., 2022). Ferrocement was developed in the mid-20th century to work on thin-shell constructions and prefabricated designs, where it was appreciated due to being much easier to mold than the conventional reinforced concrete of the same thickness, being much stronger per unit thickness, and was better at crack containment (Shaheen et al., 2023). It has found varied use due to its combination of low self-weight, simplicity to fabricate by hand and good toughness, which has allowed its use in water tanks, boat hulls, retrofitting overlays and architectural shells (Shinde et al., 2022). According to recent research, the importance of updating reinforcement approaches to enhance durability and sustainability without losing the beneficial mechanical behavior of ferrocement is

highlighted (Saeed and Hassan, 2024). The mechanical properties of ferrocement were summarized in Table 1.

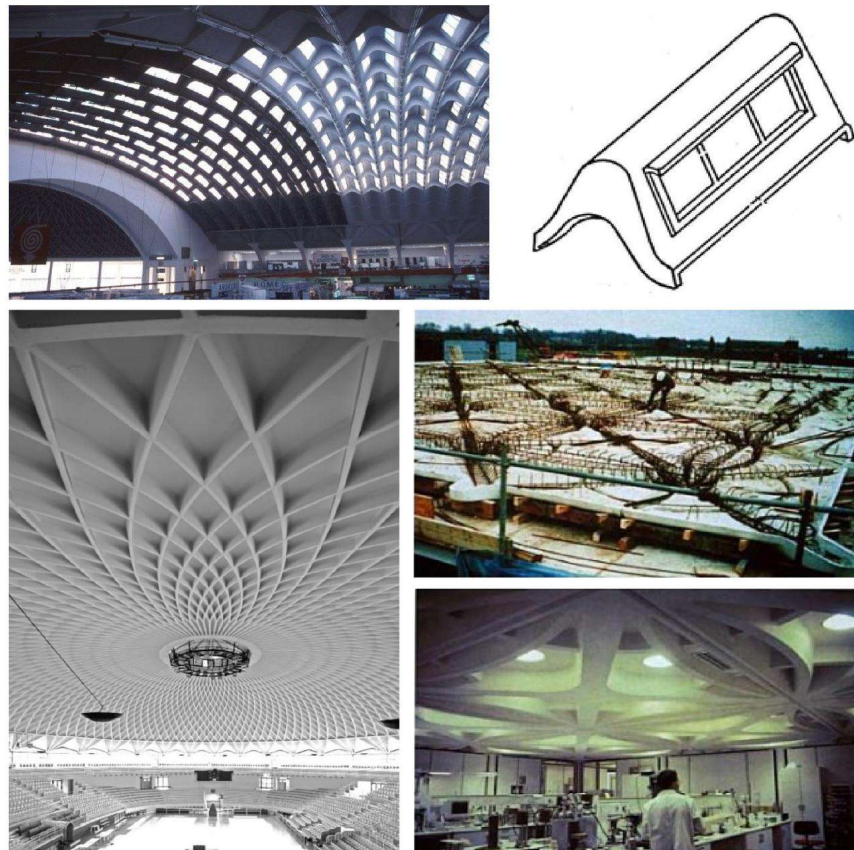
**Table 1.** Mechanical properties of ferrocement composites.

Property	Value Range	Reference
Compressive Strength	25-40 MPa	Ramalingam et al., 2022
Flexural Strength	5-10 MPa	Shaheen et al., 2023
Modulus of Elasticity	15-25 GPa	Shinde et al., 2022
Crack Width	$\leq 0.2$ mm	Saeed and Hassan, 2024

### B. Rubberized Mortar-Concrete Characteristics

The addition of crumb rubber into cementitious matrices has attracted interest because of its capability to increase toughness, impact resistance and protective measures of cracks, in addition to enhancing thermal insulation and decreasing the density of materials (Saeed and Hassan, 2024). Though compressive and tensile properties of rubberized concrete have been lower than traditional concrete, durability tests have revealed that it performed satisfactorily under freeze-thaw cycles and during contact with aggressive chemicals (Ahmad et al., 2023). Recent

records show that rubberized cementitious composites have the potential to dramatically improve the dispersion and ductile nature of cracks in case they are proportioned in the proper way (He et al., 2023). Figure 1 depicts a historical and practical example of the rubberized cementitious materials, their development, and practical use in the construction industry. Additionally, the use of recycled rubber mitigates environmental issues associated with waste tire disposal. Table 2 presents the mechanical properties of rubberized concrete.



**Figure 1** Historical and applicative illustration of rubberized cementitious composites (AbdelAleem and Hassan, 2022).

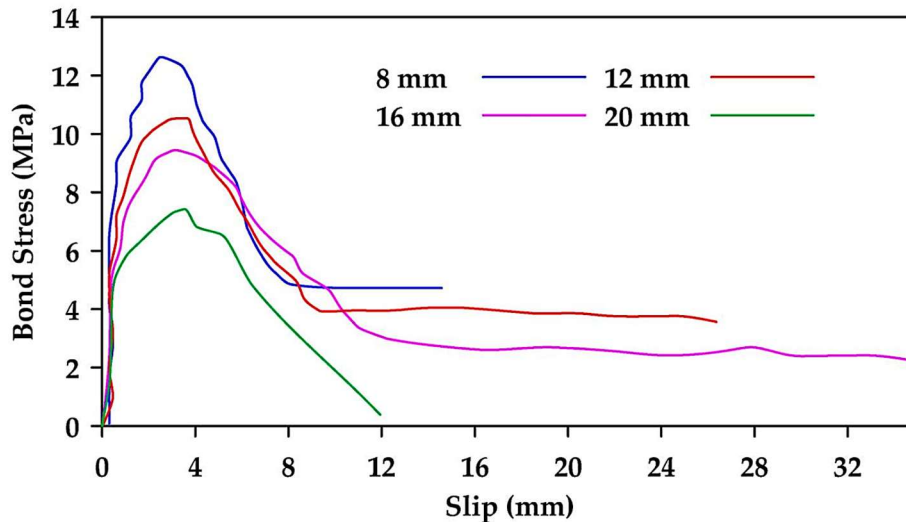
**Table 2.** Mechanical Properties of Rubberized Concrete

Property	Value Range	References
Compressive Strength	15–25 MPa	Saeed and Hassan, 2024
Tensile Strength	2–4 MPa	Ahmad et al., 2023
Flexural Strength	3–6 MPa	Ahmad et al., 2023
Density	1800–2200 kg/m <sup>3</sup>	Saeed and Hassan, 2024

C. *Glass Fiber Reinforced Polymer (GFRP) Bars Properties*  
 GFRP bars found extensive application in the reinforcement of concrete as they have a high strength-weight ratio, corrosion, and non-magnetic (Saad et al., 2025). They are high tensile strength and low modulus elasticity but lower bond strength with concrete as compared to the steel bars which may limit the structural performance. Bond behavior is enhanced using surface treatments, such as sand-coating and helical grooves. The mechanical properties of GFRP bars and the stress slips curve of their bond behavior with different diameters in concrete are in Table 3 and Figure 2, respectively.

**Table 3** Mechanical properties of GFRP bars (Saad et al., 2025)

Property	Value Range
Tensile Strength	600–900 MPa
Modulus of Elasticity	30–50 GPa
Bond Strength	5–15 MPa



**Figure 2** Stress-slip curve of bond behavior of GFRP bars in concrete (Saad, S., & Polak, 2025).

D. *Steel Wire Rope (SWR)*

Steel wire rope (SWR) is characterized by high tensile strength, ductility and post-crack excellent performance, which makes it a reasonable choice to use in energy-absorbing purposes (Wang et al., 2021). Its attachment to

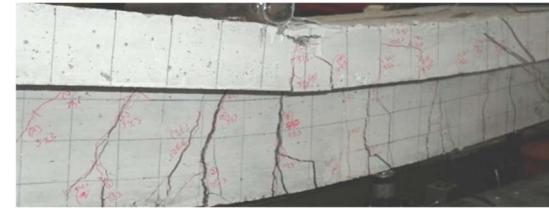
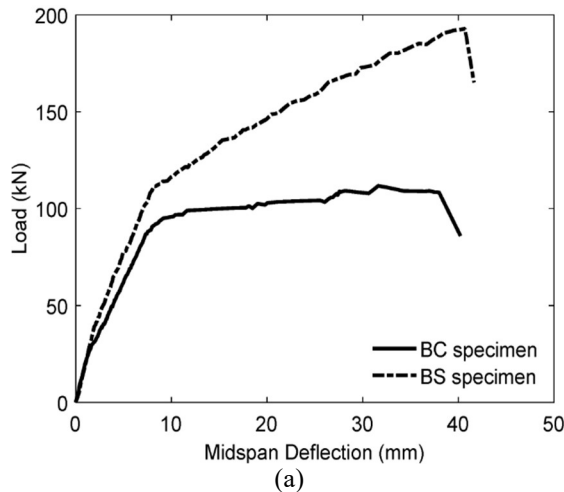
concrete may be influenced by the surface condition and corrosion and research aims to enhance adhesion by using surface treatment and protective layer (Katiyar et al., 2024). Table 4 presents a summary of the mechanical properties of SWR.

**Table 4.** Mechanical Properties of Steel Wire Rope.

Property	Value Range	Reference
Tensile Strength	1500-2000 MPa	Wang et al., 2021
Modulus of Elasticity	200-210 GPa	Katiyar et al., 2024
Ductility	High	Wang et al., 2021

Figure 3 (a-c) presents the response and collapse of unreinforced (BC) and SWR-strengthened (BS) beams. The behavior of both beams is trilinear in terms of load-deflection response, which is composed of the elastic, cracking and post-yielding response. There is increased serviceability in the BS beam with 24% increased deflection at the start of

crack and ultimately deflection, showing higher ductile and energy absorption, and its deflection at yielding is improved by a moderate percentage (8%). Concrete crushing led to the failure of the BC beam with the onset of flexural cracks at 28.20 kN and continued through the entire depth until the beam failed at 111.80 kN when the steel yielded.



(b)



(c)

Figure 3 Load-deflection curves showing post-crack behavior of SWR-reinforced concrete beams (Atmajayanti et al., 2025)

E. Hybrid Reinforcement Systems (GFRP + SWR)

Hybrid reinforcement systems based on GFRP and SWR capitalism on the corrosion resistance of GFRP, the high ductile and energy absorption properties of SWR to improve durability, serviceability and structural performance (Devaraj et al., 2023). Enhanced flexural and shear strength

of hybrid-reinforced beams is evidenced by the experimental research. Table (5) presents the comparisons between various hybrid reinforcement configurations and Figure (4) is a schematic layout of a hybrid reinforcement system of GFRP and SWR.

Table 5. Comparison of Hybrid Reinforcement Systems (Devaraj et al., 2023)

Reinforcement Type	Advantages	Limitations
GFRP + SWR	Corrosion resistance, high ductility	Lower bond strength, cost
GFRP + Steel	High strength, corrosion resistance	Higher weight, potential for corrosion
SWR + Steel	High ductility, cost-effective	Potential for corrosion, higher weight

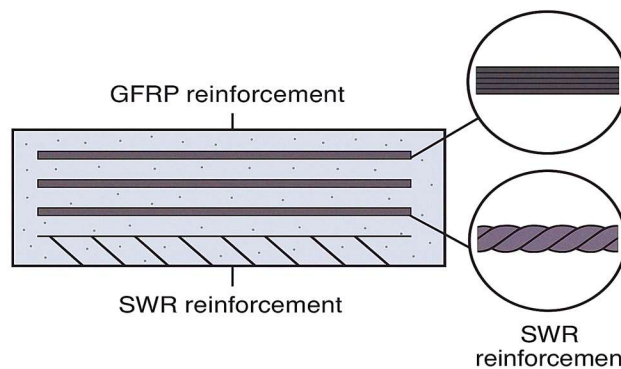


Figure 4. Hybrid reinforcement system (GFRP and SWR) configuration

III. REINFORCEMENT EFFECTIVENESS AND LIMITATIONS

This section summarizes recent experimental findings on their influence on flexural strength, ductility, bond behavior, crack control, and structural performance,

highlighting both the benefits and remaining challenges associated with each reinforcement approach.

A. Rubberized Ferrocement - Concrete

There is a relatively large amount of literature regarding the use of crumb rubber or waste tire rubber (WTR) in ferrocement and concrete materials. The recurrent

observation in literature was that rubber improves ductility, energy absorption and impact resistance but usually lowers compressive and flexural strength to a different extent based on the particle content, size and pre-treatment. Indicatively, Sharaky et al. (2020) found that 10% replacement by rubber lowered flexural capacity of reinforced beams by approximately 3.8% though this was countered by addition of welded wire mesh (WWM) reinforcement. In the same manner, Adday and Ali, (2023) affirmed that the introduction of CFRP overlays reduced flexural capacity by 17-34% by

compensating the stiffness loss in the rubberized beams. More current research by Alizadeh (2024) and Albidah (2024) considered chemically treated rubber and functional-graded systems that demonstrated that advanced processing and layered structures can reduce strength loss at the maximum ductility and toughness. Table 6 presents a brief description of some representative experimental programs and their main findings, and it can be observed that there was a balance in the ductility gains and strength losses realized in rubberized ferrocement and concrete.

**Table 6** Selected experimental studies on rubberized ferrocement and rubberized concrete

Study	Specimen / Mix	Rubber content	Key Findings
Sharaky et al., 2020	RC beams with welded wire mesh	0%, 10%, 20% CR	Flexural capacity decreased by $\approx 3.8\%$ at 10% CR; WWM mitigated the reduction, increasing capacity by $\approx 6-9\%$ and shifting failure mode to flexure.
Adnan Adday & Ali, 2023	RC beams, 5% & 10% WTR + CFRP sheets	5%, 10%	Rubber addition reduced initial strength; CFRP sheets restored stiffness and enhanced flexural load capacity by $\approx 17.1\%$ (1 layer) and $\approx 34.3\%$ (2 layers).
Ghoniem, 2024	Crumb rubber + steel fibers	5-15%	Incorporation of steel fibers improved toughness and offset the strength loss associated with rubberized mixes.
Alizadeh, 2024	Treated rubberized mixes	5-20%	Surface treatments of rubber particles improved bond characteristics and resulted in measurable strength gains over untreated mixes.
Albidah, 2024	Functionally graded rubberized beams	layered rubber/plain concrete	Flexural capacity decreased by $\approx 3.8\%$ at 10% CR; WWM mitigated the reduction, increasing capacity by $\approx 6-9\%$ and shifting failure mode to flexure.
Emara et al., 2025	Rubberized RC beams with NSM strengthening Fibrous rubberized	5%, 10%	Rubberized beams showed reduced capacity, but NSM strengthening enhanced load capacity, stiffness and improved failure modes compared to unstrengthen beams.
Li et al., 2025	concrete (NBR, silicone, EPDM fibers)	5%, 10%, 15%	Rubber fibers improved impact resistance and toughness; however, higher fiber length/content reduced compressive and flexural strength compared to plain concrete.

#### B. FRP Reinforcement in Cementitious Composites

GFRP bars used in cementitious composites have been attracting more attention because of their high tensile strength and corrosion resistance. But they have reduced elastic modules and linear-elastic rupture mode which tend to cause greater service deflections and brittle failure modes than steel. Recent research underlines that surface alterations, like sand coating or helical wrapping, have a great impact on bond behavior, and extend premature slipping failures. Illustratively, Xie et al. (2023) established that the sand-coated GFRP bars showed significantly superior anchorage when compared to smooth bars, whereas

Saad et al. (2025) and Rahman (2025) presented systematic reviews and experimental confirmation of bond-slip mechanisms. According to these results, the proper adjustments of bar surface treatment and mix design were an important factor to consider when applying GFRP to ferrocement systems, especially with low-stiffness matrices like rubberized mortar. Table 7 has provided a summary of representative studies on the bond and flexural behavior of GFRP bars which have summarized the recent knowledge on bar surface treatments, development length and serviceability issues.

**Table 7** Selected experimental studies on FRP (GFRP) reinforcement & bond (representative)

Study	Test	Focus	Key findings
Xie et al., 2023	Pull-out & beam tests (helically wrapped/sand-coated GFRP)	Bond behavior	Sand coating and helical wrapping enhanced bond strength, delayed slip and modified failure modes.
Saad et al., 2025	Review & experiments	GFRP bar bond in concrete	Bar surface, diameter, concrete strength and fiber addition critically influence bond, with practical design recommendations provided.
Rahman, 2025	Comprehensive bond study	Bond mechanisms	Systematic analysis of factors controlling GFRP–concrete bond, informing development length design.
Alsuhaibani, 2024	GFRP in columns	Compressive & bonding performance	GFRP bars effective under combined loading; proper detailing ensures acceptable bond and serviceability.
Li et al., 2025	Bond tests of GFRP bars in concrete with varying confinement	Bond mechanisms / GFRP–concrete interface	Confinement improves bond strength and reduces slip, supporting consideration in development length design.

### C. Steel Wire Rope (SWR)

SWR has also been investigated as a form of internal reinforcement, as well as external method of strengthening of ferrocement and reinforced concrete beams. It is very appealing to enhance ductility and energy absorption owing to its high tensile strength, flexibility and preferred post-cracking behavior. Kim et al. (2017) and Haryanto et al. (2021) established that external SWR reinforcement had the potential to enhance ultimate load capacity by as much as 250% based on rope design and anchorage. More recent

studies, including Atmajayanti et al. (2025), have indicated that bonded fiber-core SWR is effective in enhancing the load-bearing capacity, ductility and crack control in reinforced T-beams. Nevertheless, cyclic loading, corrosion and bond degradation are research problems. Table 8 presents the overview of the main SWR applications and structural output. It gave a comparative overview of the experimental findings on the crack control, load capacity and ductility enhancement.

**Table 8** Selected experimental studies on steel wire rope (SWR) reinforcement.

Study	Technique	Focus	Key findings & performance impact
Kim et al., 2017	External wire rope units	Shear & flexure strengthening	External rope units increased strength, with performance dependent on configuration; up to $\approx 47\%$ increase compared to baseline.
Haryanto et al., 2021	Ext. SWR for RC beams	External strengthening	Substantial improvements in ultimate load and stiffness observed; increases up to 250% reported depending on test setup.
Atmajayanti et al., 2025	Fiber-core SWR bonded to RC T-beams	Bonded FC-SWR	FC-SWR significantly enhanced load capacity, ductility and energy absorption, with notable improvements in both load and energy metrics.

### D. Hybrid Reinforcement (FRP with ductile steel systems)

In order to eliminate the deficiencies of single-material systems, new studies have been conducted on hybrid reinforcement methods that involve using FRP together with ductile steel or SWR. These systems take advantage of the high tensile strength and corrosion properties of FRP and have the advantage of yield of steel elements and energy dissipation. Nguyen et al. (2020) established that hybrid GFRP-steel beams had balanced performance to which steel yielded first and GFRP added to ultimate load capacity, thus,

improving serviceability. Adday and Ali (2023) demonstrated that, in beams of rubberized material, CFRP overlays, used with internal mesh reinforcement, were effective in compensating losses in stiffness and enhancing the post-cracking response. Newer investigations also support the view that hybrid systems of SWR + FRP have the capability of synergistic advantage, but anchorage and compatibility of the bond are important design factors. Table 9 shows the complementary behavior of FRP and SWR on the case of ferrocement and concrete systems.

**Table 9** Selected experimental studies on hybrid reinforcement

Study	Hybrid scheme	Focus	Key findings
Nguyen et al., 2020	Steel, GFRP, hybrid GFRP+steel beams	Hybrid ductility & capacity	Hybrid beams combined steel ductility and GFRP capacity; steel yielded first, followed by concrete crushing, providing good serviceability.
Adday & Ali, 2023	Rubberized concrete + CFRP + internal mesh	Hybrid for rubberized mixes	CFRP compensated for rubber-induced stiffness loss; hybrid scheme enhanced post-crack performance, increasing flexural capacity by 17-34%.
Rahman et al., 2025	GFRP bars in concrete (pull-out & bending tests)	Bond mechanisms / GFRP-concrete interface	Bar protrusion and surface properties significantly influence bond strength; results provide guidance for improved development length and bond performance.
Bao et al., 2025	FRP/GFRP bars in concrete under dynamic loading	Bond performance under dynamic conditions	Bond strength increases with higher concrete strength; dynamic loading affects performance; surface analysis explains bond variations.

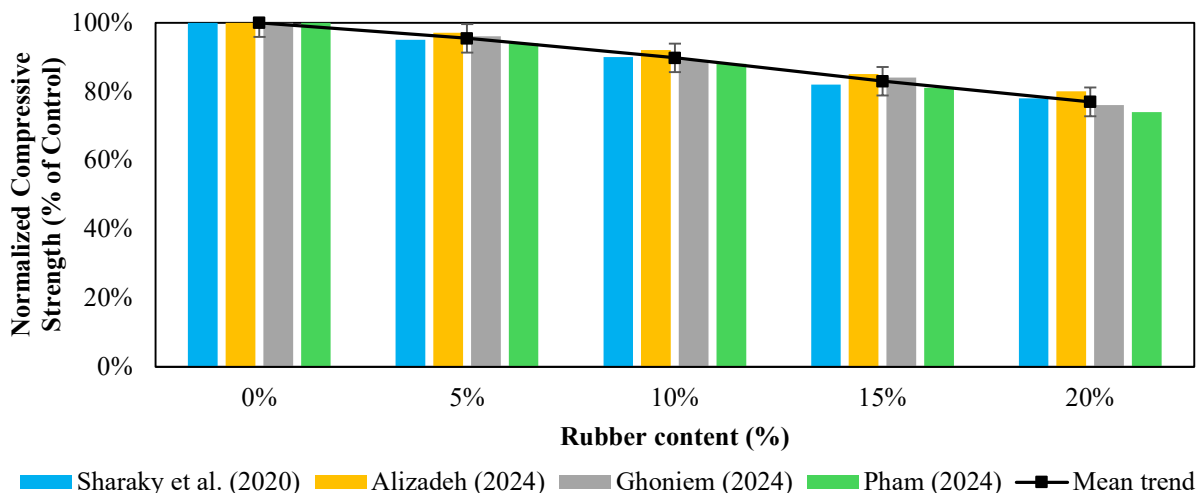
**IV. FLEXURAL PERFORMANCE**

This section discusses the influence of the reinforcement strategies on flexural strength, stiffness, bond behavior, failure modes, and serviceability, highlighting the trade-offs between strength, ductility, crack control, and structural efficiency.

*A. Flexural Strength and Stiffness*

The nature of reinforcement and use of rubber in mortar matrix was some of the factors that significantly affected the flexural performance of ferrocement beams. The results of experimental programs have repeatedly demonstrated that compressive and tensile strength decrease with the presence of crumb rubber, and thus the peak flexural capacity decreased. As an illustration, Sharaky et al. (2020) and Alizadeh (2024) introduced decreases in ultimate load by up to 5-20% of mixes 10-20% replaced with rubber. But these cuts can be alleviated through reinforcement detailing: Adday and Ali (2023) have shown that flexural strength was regained through use of CFRP overlays up to 34% and SWR and welded wire mesh reinforcements have both been shown

to add capacity. More to the point, rubberized matrices increase ductility and post-cracking deformations which allow beams to withstand greater deflection at near peak loads. This trade of strength loss and ductile gain makes the maximization of the content of rubber and the choice of the reinforcement types which can fill the mechanical weaknesses of the matrix more important. Figure 5 demonstrates the dependence of compressive strength on the percentage of rubber replacements depending on several experimental studies, which was plotted between the normalized strength and the rubber content. The findings indicate that compressive strength decreases with increase in rubber content. With replacement increasing to 5-10%, strength reduces by a moderate amount of 4-10% and higher replacement amounts of 15-20% cause greater decreases of 17-23%. This tendency is supported by the average trend in numerous studies, which shows the compromise between the use of rubber to be sustainable and the acceptable structural functioning.

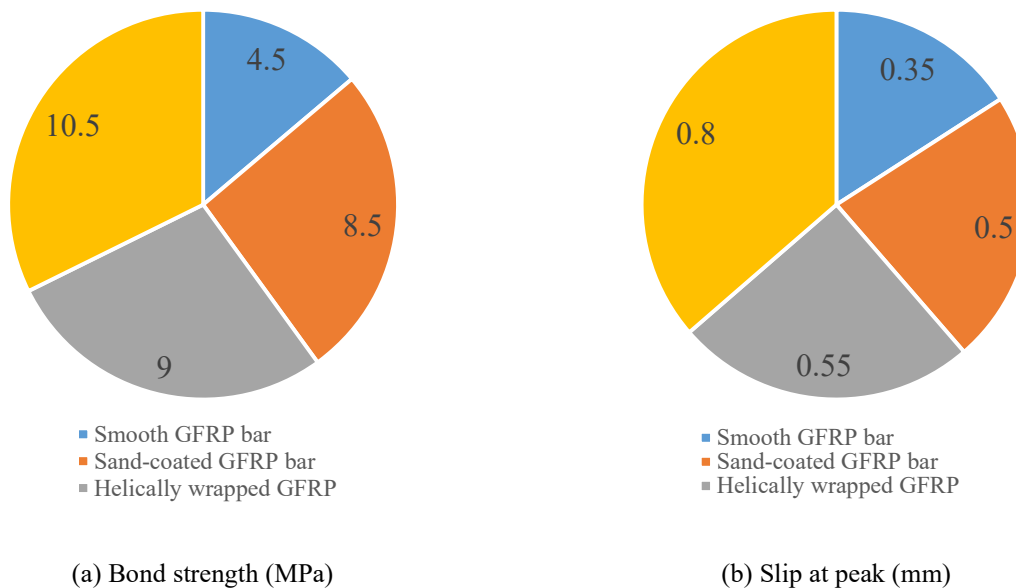


**Figure 5** Compressive strength vs. rubber replacement percentage (normalized to control).

### B. Bond Behavior and Anchorage for GFRP vs. SWR

Ferrocement beams were dependent on bond strength between reinforcement and mortar to make the action of composite. In the case of GFRP reinforcement, surface treatment, and matrix stiffness were the main factors that controlled bond behavior. The smooth GFRP bars usually have premature slip and lack of stress transfer, whereas sand-coated or helically wrapped bars have enhanced anchorage and slow bond failure (Xie et al., 2023; Saad et al., 2025). Conversely, SWR offers better mechanical interlock because of its twisted wire, which offers ease of energy dissipation and steady crack propagation. Recent works by Atmajayanti et al. (2025) have affirmed that bonded fiber-core SWRs had significant enhancement on bond strength and deflection

capacity over unstrengthen controls. But the anchorage solutions are of importance to both systems: the mechanical end anchors, the epoxy bonding tools and even hybrid types of anchorage tools were frequently needed to achieve full capacity utilization of the reinforcement. Based on the average stress-slip data that polled earlier experimental research, Figure (6) depicts a pie chart of comparative bond-slip behavior of GFRP and SWR reinforcements. The findings indicate that the strength of the bond progresses as smooth GFRP (4.5 MPa) to sand-coated (8.5 MPa) and helically wrapped GFRP (9 MPa), and SWR has the highest strength (10.5 MPa) and peak slip (0.8 mm) meaning that it showed a higher ductility and energy dissipation than GFRP bars.



**Figure 6** Bond strength and slip at peak for different types of reinforcement in rubberized mortar

### C. Failure Modes

Failure modes of rubberized ferrocement beams are highly dependent on the type of reinforcement. GFRP-reinforced beams tend to fail in a brittle mode, which is a sudden rupture or slip at the interface of the bars and usually without any serious prior notice. This was credited to the linear-elasticity characteristics of GFRP to its failure and the lower stiffness of rubberized matrices. Beams with SWR reinforcement, in turn, showed slower failure, where the rope strands begin to yield and the cracks gradually grow until a greater amount of energy is dissipated, and structural collapse occurs (Haryanto et al., 2021). Intermediate responses are demonstrated by hybrid reinforcement systems, including GFRP with SWR or CFRP overlays with internal mesh: the FRP constituents help to increase the load capacity whereas the SWR is ductile and allows to regulate the expansion of cracks. Figure 7 compares normalized load-deflection responses of the control, GFRP-reinforced, SWR-strengthened and hybrid

beams and shows that there are differences in structural performance. Control steel RC beams demonstrate moderate ductility and have the maximum load of 100% and deflection of 8 mm (Shaheen et al., 2023). GFRP supported beams exhibit reduced maximum load (85%), and minimal deflection (5 mm) and are brittle in nature (Shaheen et al., 2023). Overlays made of CFRP rubberized beams enhance strength (95%), deflection (10.5 mm) as well as moderate-high ductility (Adday and Ali, 2023). SWR-strengthened beams have a maximum 110% of the control load with a 12 mm deflection, indicating high ductility (Haryanto, 2021), whereas beams with hybrid SWR + GFRP/CFRP have the best performance, with a 120% peak load and 11 mm deflection, showing high to very high post-peak ductility (Atmajayanti, 2025). An important point in these results is the increased strength, deformation capacity and energy absorption of SWR and hybrid strengthening methods.

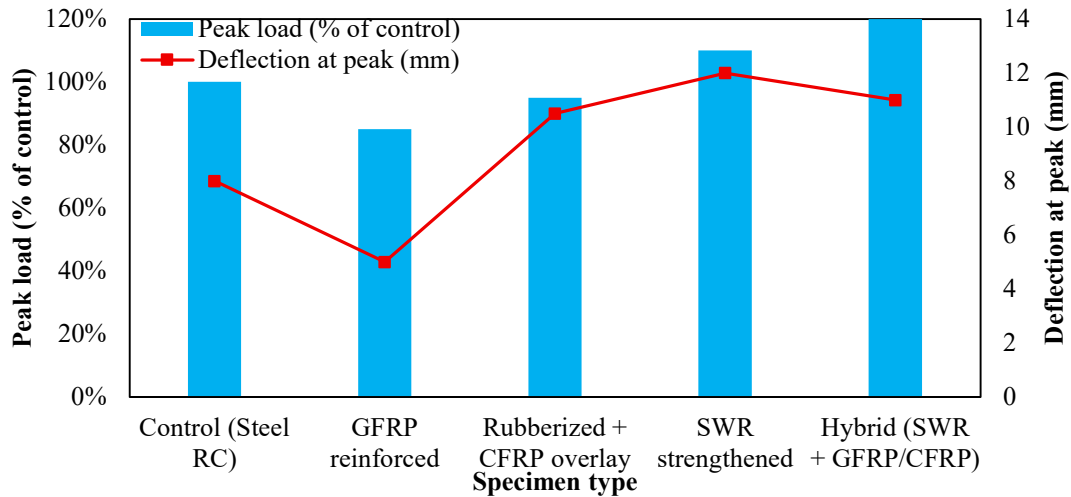


Figure 7 Normalized load-deflection behavior for representative specimens.

#### D. Serviceability Considerations

Ferrocement beams were critically designed as to serviceability, especially when rubberized matrices and FRP reinforcements were used, since they have lower stiffness and they can deflect more and have larger cracks under service loads (Shaheen et al., 2023). Figure 8 draws a comparison of the various reinforcement systems. The traditional steel restricts the average width of cracks to 0.3 mm under 40% of the intended load (Xie et al., 2023), and GFRP-reinforced beams have broader cracks of 0.55 mm because of brittle behavior (Haryanto, 2021). SWR

reinforcement decreases the cracks widths to 0.35 mm with ductile yielding and high bond performance and hybrid system with SWR and CFRP overlays generate the most performance with cracks widths reduced to 0.25-0.30 mm and works with improved stiffness retention and serviceability in rubberized beams (Haryanto, 2021; Adday & Ali, 2023). The results demonstrate the benefits of the SWR and hybrid reinforcement schemes in sustaining structural integrity with the limitation of service-load deformations.

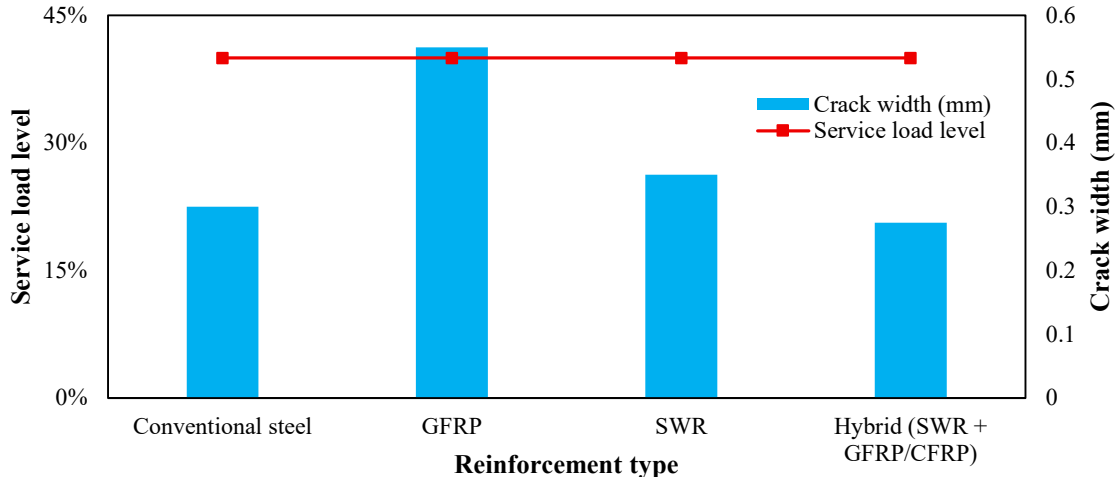


Figure 8. Crack widths at service load ( $\approx 40\%$  of ultimate) for different reinforcement types.

## V. ANALYTICAL AND NUMERICAL MODELING APPROACHES

This section reviews the principal analytical and numerical approaches used to predict the flexural behavior of rubberized ferrocement members. It summarizes empirical equations, analytical formulations, and finite element modeling techniques employed to evaluate flexural strength, moment–curvature response, bond behavior, and structural performance, while highlighting their applicability and limitations for rubberized and hybrid-reinforced systems.

#### A. Empirical Equations for Flexural Strength

The initial research on ferrocement and FRP-reinforced composites was based on empirical equations based on experimental research in estimating flexural capacity. These models generally gave ultimate moment in terms of reinforcement ratio, tensile strength of reinforcement and compressive strength of mortar (Haryanto, 2021; Xie et al., 2023; Alsultani and Nahi, 2026). But compressive and tensile strength can be reduced in rubberized ferrocement, necessitating alteration of these models. The recent research

(Sharaky et al., 2020; Alizadeh, 2024; Ali et al., 2026) has suggested the strength-reduction factors that depend on the percentage of replacing rubber. Empirical key models and

their feasibility to rubberized ferrocement are summarized in Table 10.

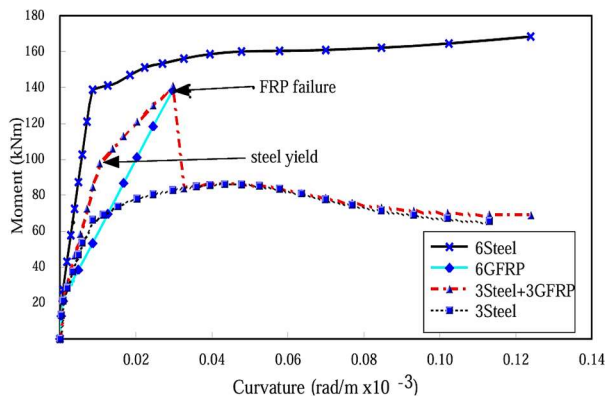
**Table 10.** Empirical equations for flexural strength of ferrocement and rubberized composites

Base Equation	Key Parameters	Rubberized Adaptation	Reference
$M_u = A_s f_y \left( d - \frac{a}{2} \right)$	Steel ratio, depth	Not included	Xie et al. (2023)
$M_u = A_{frp} f_{frp} d (1 - 0.5k)$	FRP stress, depth	Not included	Haryanto (2021)
Modified steel eqn.	Rubber %, mesh ratio	Strength reduction factor $R = 0.9 - 0.02r$	Sharaky et al., 2020
Empirical regression	Rubber %, GFRP modulus	Linear regression models	Alizadeh, 2024

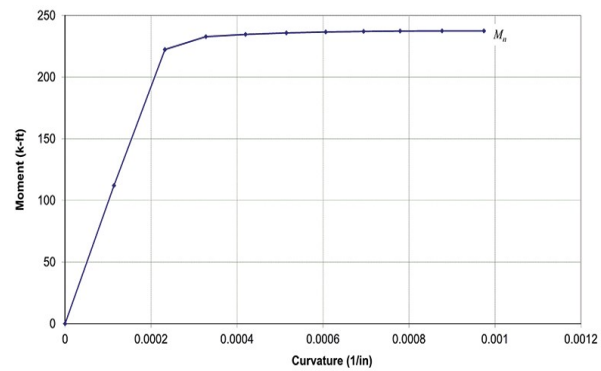
**B. Analytical Models**

Still popular to predict flexural behaviour are the analytical models that rely upon sectional analysis and equilibrium. The methods calculate moment-curvature ( $M - \phi$ ) equations by imposing force equilibrium in compression and tension zones and using linear-elastic or bilinear reinforcement behavior (Nehdi and Said, 2015; ACI 549, 2018; Saad et al., 2025). In the case of GFRP reinforcement, the assumption

was linear stress-strain till rupture, whereas in the SWR case elastic-plastic response were taken. Avoidance of reduced modulus and compressive strength values were incorporated to give rubberized mortar. A comparison of a typical M- 0 curve in steel, GFRP and SWR reinforcement systems would be as shown in Figure 9 (a and b).



(a) Steel and GFRP (Nehdi and Said, 2015)



(b) steel and SWR (Sharma et al., 2022).

**Figure 9** Representative moment–curvature ( $M-\phi$ ) curves for beams with steel, GFRP and SWR reinforcement

**C. Finite Element Modeling (FEM)**

A more sophisticated simulation of rubberized ferrocement beams is offered by Finite Element Models (FEM) taking into consideration nonlinear constitutive laws of materials, bond-slip effects and crack propagation. FRP-reinforced composites have been modeled using commercial packages like ABAQUS and ANSYS, although more current research

(Adday and Ali, 2023; Xie et al., 2023) also involves SWR reinforcement and explicit bond-slip interface elements. The modeling of rubberized matrices was done with nonlinear compressive stress-strain relationships, and lower fracture energy (Alsultani et al., 2023). Table 11 presents an overview of some of the representative FEM studies and their modeling assumptions.

**Table 11.** FEM modeling strategies for rubberized ferrocement beams.

Software	Materials Model	Bond-Slip Law	Validation Parameter	Reference
ABAQUS	Concrete Damaged Plasticity (CDP)	Perfect bond	Load-deflection	Shaheen et al. (2023)
ANSYS	Nonlinear elastic-plastic	Bond-slip interface	Crack patterns	Xie et al. (2023)
ABAQUS	Rubberized mortar model	Cohesive zone model	Flexural capacity	Adday & Ali (2023)
ANSYS	Plastic damage	Bonded SWR model	Deflection, crack width	Atmajayanti et al. (2025)

## VI. SUSTAINABILITY, PRACTICALITY AND COST IMPLICATIONS

This section evaluates the environmental benefits of incorporating recycled rubber, the cost-effectiveness of different reinforcement strategies, and the practical considerations affecting their implementation and long-term performance in structural applications.

### A. Environmental Benefits of Rubberized Mortar

Ferrocement with crumb rubber can deal with the environment and mechanical issues. Rubberized mortar means less utilization of natural aggregates, less waste tires in landfills and less carbon footprint of cement manufacture because it allows replacing part of fine aggregates (Ghaleh et al., 2025; Tanhadoust et al., 2023). On top of sustainability, rubber particles increase impact strength, vibration absorption, and post-cracking deformation, which were of specific interest to infrastructure susceptible to dynamic or seismic forces (Qaidi et al., 2021). Rubberized mortar will reduce the aggregate use by 105% of traditional mortar, which will help in conserving resources (Ghaleh et al., 2025). There was a 5-10% reduction in CO<sub>2</sub> emissions, which is in line with the global sustainability targets (Farahzabi et al., 2024). Moreover, 5-15% of waste tires were also redirected out of landfills, which reduced pollution to the environment (Ahsan et al., 2023). Another characteristic of rubberized mortar is that the toughness of the material increased by 20-40%, which improves the durability and mechanical performance of the material (Qaidi et al., 2021). The results emphasize two advantages of rubberized mortar, which contributes to environmental sustainability due to the use of waste tires, and possesses superior mechanical properties of infrastructure components (Ghaleh et al., 2025; Tanhadoust et al., 2023).

### B. Cost-Effectiveness of Hybrid Reinforcement

A compromise between cost, durability and ductility is achieved with hybrid reinforcement systems based on GFRP and SWR. GFRP bars were the priciest (400-600 USD/m<sup>3</sup>) but have corrosion resistance and a lengthy service life (50-75 years) and low maintenance needs (Chavhan and Wankhade, 2021). They were cheaper (180-250 USD/m<sup>3</sup>) and had a moderate maintenance and service life, ranging between 40 and 60 years, and high ductility and post-cracking energy absorption (Mashayekhi et al., 2024). Traditional steel was cheaper (150-200 USD/m<sup>3</sup>) but it needs medium maintenance, and its expectancy of service is 30-50 years. Hybrid GFRP and SWR systems cost 450-650 USD/m<sup>3</sup>, service life is 50-70 years and low maintenance and take advantage of both materials to ensure better structural performance and cost-effectiveness over the long term (Ribeiro et al., 2024).

The use of the rubberized ferrocement with the hybrid reinforcement is sensitive to constructability to inspire the desired structural performance were met. The anchorage required was critically important because neither of the GFRP bars nor the SWR should be of inadequate development length when they are fully mobilized. The rubberized mortar had to be properly placed too to avoid the problems of rubberized mortar segregation or floating which

may jeopardize the mechanical performance of the composite. Further, the quality of workmanship would also be required, including high accuracy in designing the meshes of wires, ropes and FRP bars, so that the projected flexural performance and crack-control features would be achieved.

## VII. IDENTIFIED RESEARCH GAPS

Although the research of rubberized ferrocement reinforced with hybrid systems has achieved significant success, there are still some critical research factors that have not been met and are to be addressed to ensure that the potentials of these novel composites are fully achieved. To begin with, there were few studies on large-scale structural applications. Most of the literature is done on small or medium-size specimens and hence cannot be extrapolated to full-scale beam, slab or structure under realistic service loads, complicated boundary constraints and load combinations. Second, long-term durability is the field in which systematic research is needed. Whereas the corrosion resistance of GFRP and the ductility of SWR had been well-characterized separately, the interaction of the two components in the presence of rubber-modified matrix under long-term conditions of exposure to environmental aggressors, including moisture, chlorides, freeze-thaw cycles and chemical attack has not been characterized comprehensively. Equally, time-dependent processes such as creep, shrinkage and fatigue in such hybrid systems have not been studied extensively, but were extremely important in predicting long-term structural processes and serviceability.

Third, seismic and cyclic performance of rubberized ferrocement beam with hybrid systems have not been explored strictly. The knowledge of energy dissipation, ductility and damage tolerance under dynamic or repeated loading was required in the application to the earthquake prone areas or the infrastructure of the structures under vibrational loads (Alsultani et al., 2025a; Alsultani et al., 2025b). This type of study was of special interest to hybrid systems, in which the interactions between GFRP and SWR can affect the progressive yielding, crack propagation and failure mechanisms in a manner that is not identical to normal steel reinforcement. Fourth, better bond modeling is another important field to study. The interaction was complex between the rubber and GFRP and SWR and it controls the transfer of stress, crack control and ultimate flexural capacity. Current analytical and finite element models tend to model or oversimplify these interactions, and this might restrict the level of accuracy in serviceability, deflection and failure mode prediction. Experimental data coupled with detailed investigations using refined numerical modeling was required to have reliable design formulations.

Lastly, extensive life cycle and sustainability analysis were badly required. Although the use of recycled rubber encourages environmental advantages, a comprehensive assessment that considers mechanical performance, durability, embodied carbon, cost and maintenance specification was now absent. These tests would offer important recommendations to both engineers and policymakers, allowing the application of evidence-based design principles and promote the use of sustainable hybrid

ferrocement systems in practice. Altogether, it can be stated that covering these gaps in research will not only deepen the insights about the rubberized ferrocement with hybrid reinforcement but also serve as the basis of further development of effective design principles, efficient use of materials and creation of strong, viable infrastructure solutions.

### VIII. CONCLUSION

This paper presented a comprehensive review of rubberized ferrocement beams reinforced with hybrid Glass Fiber Reinforced Polymer (GFRP) bars and steel welded reinforcement (SWR), examining their structural performance, durability characteristics, and potential sustainable applications. The findings indicate that the incorporation of rubber particles enhances ductility, energy absorption capacity, and crack resistance, although it may reduce compressive and flexural strengths; however, these strength reductions can be effectively mitigated using hybrid reinforcement systems. Surface treatment methods were found to improve the bond performance of GFRP bars, while SWR provides superior mechanical interlocking and enhanced post-cracking stability. The hybrid GFRP–SWR reinforcement system also improves serviceability by reducing deflections and controlling crack widths under loading conditions. Furthermore, nonlinear finite element models incorporating bond–slip relationships have demonstrated good accuracy in predicting the flexural behavior of hybrid ferrocement beams. The review further highlights the importance of proper reinforcement placement and mortar handling during construction to achieve the expected structural performance. From a sustainability perspective, rubberized ferrocement beams reinforced with hybrid GFRP–SWR systems offer significant advantages, including reduced self-weight, improved corrosion resistance, and the beneficial utilization of waste rubber materials. Nevertheless, research on large-scale implementation, long-term durability, seismic performance, and life-cycle assessment remains limited. Overall, rubberized ferrocement beam systems reinforced with hybrid GFRP–SWR composites show considerable promise for modern civil infrastructure applications requiring lightweight, durable, corrosion-resistant, and energy-dissipative structural elements, although further experimental, numerical, and field investigations are necessary to address existing knowledge gaps and support their widespread adoption.

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#### List of Acronyms

ACI	American Concrete Institute
BC	Unreinforced (Control) Beam
BS	Steel Wire Rope-Strengthened Beam
CDP	Concrete Damaged Plasticity
CFRP	Carbon Fiber Reinforced Polymer
CO <sub>2</sub>	Carbon Dioxide
CR	Crumb Rubber
EB	Externally Bonded
EPDM	Ethylene Propylene Diene Monomer
FC-SWR	Fiber-Core Steel Wire Rope
FEM	Finite Element Modeling / Finite Element Model
FRP	Fiber Reinforced Polymer
GFRP	Glass Fiber Reinforced Polymer
MPa	Megapascal
NBR	Nitrile Butadiene Rubber
NSM	Near Surface Mounted
RC	Reinforced Concrete
SWR	Steel Wire Rope
WTR	Waste Tire Rubber
WWM	Welded Wire Mesh