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COMPARATIVE ANALYSIS OF NOVEL SUSTAINABLE STRENGTHENING TECHNIQUES FOR REINFORCED CONCRETE SLABS: A REVIEW OF NOVEL TECHNOLOGIES

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ABSTRACT. This research review presents a comprehensive examination of recent advancements in strengthening techniques for reinforced concrete (RC) slabs, with a focus on enhancing structural performance under critical conditions such as punching shear, flexural loads, thermal exposure, corrosion, and impact. The studies analyzed explore both traditional and innovative materials and configurations, including externally bonded aluminum sheets, embedded aluminum sections, CFRP and GFRP composites, textile-reinforced mortar (TRM), strain-hardening cementitious composites (SHCC), ferrocement strips, and ultra-high-performance concrete (UHPC). Experimental investigations across the reviewed papers reveal that these strengthening strategies significantly improve load-carrying capacity, ductility, energy absorption, and stiffness, with some configurations restoring or exceeding original structural performance. Special attention is given to slabs with service openings, fire-damaged concrete, and blast or projectile loading, where hybrid systems such as NSM-CFRP ropes and UHPC overlays proved especially effective. Analytical and finite element models validated these results, supporting their application in both retrofitting and new construction. Collectively, the studies offer practical insights for engineers seeking to extend service life, enhance safety, and address deterioration in RC slabs, providing a valuable foundation for future structural strengthening initiatives.

KEYWORDS: *RC slabs; Strengthening; Externally Bonded Reinforcement; Near Surface Mounted; High-Performance Concretes; Structural Analysis*.

1. INTRODUCTION

Structural elements such as Reinforced Concrete (RC) slabs form the essential framework of multiple construction projects, which include buildings and bridges, and parking facilities [1–5]. The performance of these slabs requires reinforcement throughout their service life because of demanding loads and material decay, and improper designs. Research work has extensively analyzed multiple approaches to boost the effectiveness of RC structures through enhancements to bending performance and shear resistance, and extended overall service life [6–15]. The evaluation of RC slabs for residential and highway bridge applications shows their durability through the combination of material characteristics and service load requirements [16,17]. The time-dependent increase in occupancy load intensity, together with use modifications and environmental degradation via chloride infiltration and freeze-thaw phenomena alongside original design constraints, leads to performance deficiencies in existing slabs regarding flexural as well as shear and punching-shear capabilities [18,19]. The research community has spent the last twenty years researching multiple strengthening approaches that aim to restore or exceed the original capacity specifications of slabs. These strategies provide dual benefits of extended lifetime with enhanced safety features and enhanced resource efficiency through minimized requirements for full demolition and reconstruction [1,20–29].

The original studies involving externally bonded (EB) fiber-reinforced polymer (FRP) systems showed that attaching thin FRP laminates to slab tension faces through epoxy achieved substantial flexural strength improvements in one-way panels up to 50 percent [30–40]. The initial research by Triantafillou and Deskovic demonstrated that CFRP sheets move the neutral axis position and activate supplementary tensile reinforcement until either FRP rupture or concrete crushing causes failure [41]. Research shows that bond performance under cyclic or fatigue loading together with epoxy softening at temperatures exceeding 60 degrees Celsius and improper surface preparation and anchorage details create premature debonding risks at the FRP–concrete interface. The implementation of analytical modeling allowed researchers to develop more accurate predictions of debonding loads through refinements of bond–slip relationships while field tests on parking-garage slabs demonstrated the method's practicality when environmental exposures receive protection from protective coatings [42–48].

The NSM FRP method appeared when FRP rods or strips were placed within concrete grooves and then refilled with grout to achieve improved bond strength and durability [49,50]. Research work conducted by Diab and sayed [51] included systematic variation of fiber type along with groove depth and anchorage length to discover the most effective configurations which showed shear-capacity improvements of 25 % to 40 % in RC beams and slabs while avoiding debonding failures experienced by EB-FRP systems. Researchers have developed prestressed NSM rods (PNSM) through which they apply initial tensile force before embedding to activate compressive membrane action (CMA) during flexural testing which results in shear capacity improvements of up to 70 % with minimal reinforcement ratios [52–55]. The PNSM method demonstrates excellent prospects yet it faces two key challenges of maintaining prestress integrity over time and performing precise groove cutting in dense reinforcement locations particularly at slab-beam connection points.

Fire resistance and polymer-compatibility issues in compound systems led experts to test Textile-Reinforced Mortar (TRM) composites which consist of high-strength fiber grids (carbon, AR glass and PVA) embedded in inorganic mortar matrices [56–58]. A research team led by Lampros Koutas and Bournas investigated the effects of TRM strengthening on two-way RC slab strips in a series of four-point bending tests up to three layers [57]. The researchers discovered that TRM strengthened structures achieved a 30%–45 % enhancement of flexural moment capacities through minimal thickness addition compared to epoxy systems which have bond-slip problems. The analysis by Louter and his team demonstrated that short PVA fibers in mortar decrease shrinkage cracks while enhancing composite ductility which is necessary for slabs that experience repeated load changes [59]. The implementation of TRM systems for shear strengthening involves placing these systems around column strips to lower punching-shear critical regions through stress redistribution [60].

When using fiber-reinforced cementitious matrix (FRCM) systems, textile grids combine with cementitious mortars that provide high vapor permeability and are unsaturated in their independent form [61,62]. Researchers Tamborrino et al. [63] conducted tests on FRCM-concrete bond through pull-off testing which demonstrated equal bond strength to EB-FRP but better performance in high temperature and moisture testing. Researchers have successfully implemented these systems on bridge-deck slabs to counteract traffic-induced fatigue which destroys external adhesives; FRCM overlays restore flexural capacity while also delivering a host of concrete protective wearing surfaces. Research conducted by Younis and colleagues [64]about FRCM for shear strengthening demonstrated that beam shear capacity could increase up to 60 percent, while concluding that these mortar-based systems require basic field-applied equipment.

The in-plane arching effect known as CMA occurs during retrofits because it is a basic principle of restrained slab behavior [65,66]. Robinson et al. [67] employed nonlinear finite-element analysis to prove that minor in-plane support framing stiffness produces up to 25 percent additional flexural strength through CMA, which becomes more beneficial with external strengthening. Field tests on bridge-deck panels showed that pre-compression of slabs (via PNSM or tendon stressing) enhances CMA performance to reduce deflections during live loads. Arching action models now exist in design guidelines, which allow engineers to develop strengthening plans that combine internal prestressing with external reinforcement and concrete overlays for optimal results.

The comparison between different research methods has exposed the inherent advantages and disadvantages of each. Clarke's foundational study presented EB-FRP, NSM, TRM, FRCM, and UHPFRC overlays through which he discovered that EB-FRP achieves the best strength-to-weight ratio while TRM and FRCM perform better in terms of fire resistance and durability; UHPFRC delivers comprehensive structural benefits but demands a higher price tag; and NSM demonstrates a satisfactory bond balance with acceptable installation requirements. Studies that considered life-term expenses showed that NSM and TRM systems provide the most beneficial cost-effectiveness for moderate strengthening up to 30% increased facility capacity, but UHPFRC systems and PNSM–FRP hybrids become better choices for 50% capacity enhancement in critical infrastructure.

The research community focuses on developing sustainable approaches [68–75]while implementing advanced monitoring techniques. Testing shows that bio-based fibers such as flax and basalt provide TRM and FRCM systems with 15%–20 % reduced environmental impact while maintaining their strength [76]. The technology of embedding fiber-optic sensors into FRP and UHPFRC overlays has become increasingly popular because it allows real-time monitoring of strain and crack formation throughout the service life of slabs. Future research will develop machine-learning models that predict debonding and crack initiation to enhance design code precision for probabilistic retrofit assessment under uncertain environmental and loading conditions. The combined results of over thirty peer-reviewed experimental, analytical, and field investigations establish a comprehensive framework of methods that enhance the strength of RC slabs. The selection of these methods for target capacity gains needs to account for environmental exposure alongside fire and fatigue requirements and installation restrictions, and life-cycle economics [77–79].

This study aimed to analyze some previous studies [80–94] about ways to enhance RC slabs through traditional and new approaches. The strengths and weaknesses of different methods, while concentrating on sustainability methods that improve slab performance and cost-effectiveness, have been examined. The study provided a complete analysis of different strengthening techniques that aim to establish practical usage in the future. It evaluates various studies, comparing their findings and failure patterns to determine the most effective approaches for enhancing the durability and lifespan of concrete slabs. By analyzing key performance metrics and structural behavior, the research aims to identify optimal reinforcement methods that contribute to improved structural integrity and sustainability.

2. DATABASE FOR PREVIOUS STUDIES FOR HPCS

2.1. APPLICATION OF HPCS

As shown in Table 1, the study by Elsamak et al. [80] investigates experimental methods for using anchored ferrocement strips to strengthen two-way RC slabs. Scientists tested an original technique which would increase the bending strength of two-way RC slabs. The researchers connected ferrocement strips through anchorage and epoxy bonding to the tensile face of slab structures. Researchers conducted experimental tests on slab samples subjected to bending forces to determine the performance enhancement provided by this strengthening approach. The research primarily assessed how the strips increased the load-bearing capabilities and flexibility of the slabs. The experimental program investigated two-way RC slabs measuring 1000 mm × 1000 mm × 120 mm as shown in Fig. 1, strengthened using NSM ferrocement strips. Each slab was reinforced with steel bars—seven 10 mm diameter bars per meter at the bottom and six 10 mm diameter bars per meter at the top. The slabs simulated negative moment zones between contraflexure points. The test matrix included three groups: G1 (orthogonal strips without anchors), G2 (diagonal strips without anchors), and G3 (anchored orthogonal and diagonal strips). Within each group, specimens were further divided based on the number of wire steel mesh (WSM) layers—either one or two as shown in Fig. 1. The aim was to evaluate how strip orientation, the presence of anchorage, and the number of WSM layers influenced flexural performance. The program allowed for a detailed comparison of strengthening techniques, offering insights into optimal configurations for improving RC slab capacity and ductility.

Table 1. Studies examined application of HPCs in RC slabs.

Study	Year of work	Dimensions		Compressive strength (MPa)	Upper reinforcement	Lower reinforcement	Used strengthening concrete	Testing type
		Width (mm)	Thickness (mm)					
Elsamak et al. [80]	2025	1000	120	30	6 D 10	7 D 10 / m	SHCC	Flexural
Ghalla et al. [81]	2025	1000	120	32	6 D 10	7 D 12 / m	SHCC	Punching
Saeed et al. [84]	2024	1500	150	34.8	-----------	7 D 12 / m	UHPFRC	Punching
Phan et al. [85]	2025	1400	65	34.7	-----------	8 D 12 / m	UHPR$_u$C	Flexural
Essam et al. [86]	2025	1500	120	35	-----------	5 D 10 / m	SHCC	Flexural
Sun et al. [87]	2023	1600	120	30	-----------	8 D 12 / m	UHPC	Flexural
Wang et al. [88]	2025	1000	100	37.08	-----------	7 D 10 / m	UHPC	Punching
Jian et al. [93]	2023	1000	100	35	-----------	5 D 10 / m	UHPC	Punching

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The research conducted by Ghalla et al. [81] focused on assessing the performance of two-way RC flat slabs which used SHCC drop panels. The authors evaluated how SHCC drop panels boost the punching shear resistance of two-way RC flat slabs through their study. The testing procedure consisted of examining slab samples which contained and lacked SHCC drop panels during punching shear tests. The investigation sought to measure the load-carrying capacity and ductility benefits of adding SHCC drop panels to flat slabs as shown in Fig. 2. The experimental data showed that incorporating SHCC drop panels into the construction of slabs effectively improved their punching shear performance levels in a manner which could prevent RC flat slabs from failing under punching loads. This study examined ways to enhance the punching resistance of square RC slabs through experimental testing. Nine two-way flat slabs, each 1.00 m^2 and 120 mm thick as shown in Table 1, were simply supported with a 900 mm span and loaded centrally. Bottom reinforcement used U-shaped deformed steel bars, while the top zone had straight bars with wider spacing. The impact of SHCC drop panels, reinforced with GFRP mesh or GSM, was tested across four groups. Variations included panel thickness (20 mm or 40 mm) as shown in Fig. 2, reinforcement type, and anchor bolts. One control slab was compared to strengthened slabs to evaluate improvements in punching shear resistance.

The study conducted by Saeed et al. [84] on RC slabs strengthened with EB/NSM CFRP in HSC Layers focused on evaluating the effectiveness of EB and NSM techniques in enhancing the flexural performance of one-way RC slabs. The experimental program included testing slab specimens with EB and NSM CFRP reinforcements, as well as bonded reinforced HSC layers. The results indicated significant improvements in load-carrying capacity and ductility for the strengthened slabs, with the NSM technique showing higher load efficiency than the EB method. This study introduced a new method for strengthening RC slabs using CFRP rods and an UHPFRC jacket, secured with a Mechanical Anchorage System (MAS). Three slabs were tested: a control, one with a UHPFRC jacket, and another with CFRP bars embedded in the jacket.

Vu To-Anh Phan et al. [85] conducted a study on enhancing shear strength and vibration characteristics of ultra-high-performance rubberized concrete ($UHPR_uC$) slabs using stay-in-place (SIP) formworks. The research examined bridge slabs integrated with square hollow or Y-shaped stiffeners. Four slabs were tested: two with dimensions 1400 mm × 600 mm × 75 mm without glass fiber-reinforced polymer (GFRP) SIP formwork, and two measuring 1400 mm × 600 mm × 65 mm with GFRP SIP formwork as shown in Table 1. Samples were assessed for damping ratio and flexural capacity, using cyclic loads applied via accelerometers and load cells. Results showed that incorporating 20% crumb rubber improved damping ratio by 1.5 times, while Y-shaped stiffeners significantly enhanced shear resistance. $UHPR_uC$ slabs cast on SIP formworks demonstrated a **60-91% improvement** in capacity over traditional concrete slabs. The study validated $UHPR_uC$ as a promising material for resilient and durable bridge construction.

Essam Khaled et al. [86] studied the flexural behavior of RC slabs strengthened with textile-reinforced strain-hardening cementitious composites (TR-SHCC) under post-strengthening corrosion. The research involved 16 RC slabs, each 120 × 375 × 1500 mm. Four groups were tested: one unstrengthened, while others had TR-SHCC layers of 20 mm (externally bonded) or 20/35 mm (near-surface embedded) as shown in Table 1. After curing, three slabs per group underwent accelerated corrosion for 10, 20, or 30 days. A four-point bending test evaluated flexural behavior, revealing that externally bonded TR-SHCC lost efficiency under corrosion, while near-surface embedded SHCC significantly reduced deterioration. The full SHCC-replaced cover was most effective in preserving strength and reducing crack growth. A predictive model accurately estimated flexural capacity post-corrosion, supporting TR-SHCC as a reliable strengthening technique.

Xiugui Sun et al. [87] investigated the flexural behavior of hollow slab girders strengthened with UHPC through full-scale field experiments and finite element (FE) analysis. The study examined two girders: an unreinforced one and a reinforced girder with a 50 mm UHPC layer. Both girders had dimensions of 16 m × 0.9 m × 0.7 m and were tested using four-point bending tests as shown in Table 1. Strain gauges and displacement sensors measured deformation and load response. Results indicated that UHPC significantly increased flexural stiffness, raising cracking and ultimate loads by 11.5% and 23.7%, respectively. The reinforced girder exhibited improved ductility and reduced concrete crushing.

FE models verified these findings and further analyzed the effects of UHPC thickness and prestress. The study concluded that UHPC reinforcement is an effective method to enhance the structural performance of damaged hollow slab girders.

Jiyang Wang et al. [88] examined the effects of 630 MPa high-strength rebar (T63) and UHPC on the blast resistance of RC slabs under contact explosions. Five slabs 1000 mm × 1000 mm × 100 mm as shown in Table 1 with varying reinforcement ratios and materials were tested under different blast load equivalents (50g to 200g). The slabs were evaluated for macroscopic damage, crack development, and strain response using accelerometers and strain gauges. Results showed that T63-reinforced slabs exhibited reduced damage and lower peak acceleration responses compared to conventional HRB400-reinforced slabs as shown in Fig. 3. UHPC slabs demonstrated superior blast resistance, minimizing concrete spalling and preventing perforation. Existing damage prediction models underestimated the explosive resistance of T63/UHPC slabs, highlighting the need for improved prediction methods. This study confirms the effectiveness of T63 rebar and UHPC in enhancing blast resistance for civil air defense structures.

Jian Liu et al. [93]conducted a numerical study on the high-velocity projectile impact (HVPI) resistance of RC slabs strengthened with UHPC. The research analyzed 180 mm thick RC slabs reinforced with UHPC layers. Simulations explored various configurations, including steel rebar layers, grid spacing, UHPC layer positioning, and the effects of compressive strength, projectile mass, and nose shape as shown in Table 1. The study determined that placing UHPC directly on the impact face was the most effective strengthening strategy. Finite element models validated the ballistic performance and optimized UHPC placement. The slabs were subjected to parametric investigations on projectile velocity and perforation resistance, resulting in an empirical formula predicting the ballistic limit based on UHPC strength, projectile velocity, and mass. Findings confirmed that UHPC significantly enhances impact resistance, making it a reliable solution for protective structures against extreme dynamic loads

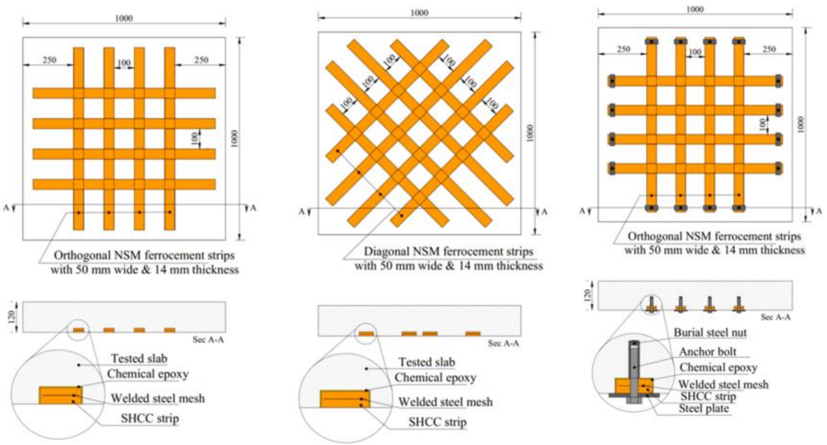

Fig. 1. Anchored and epoxied ferrocement strips used for strengthening punching [80]

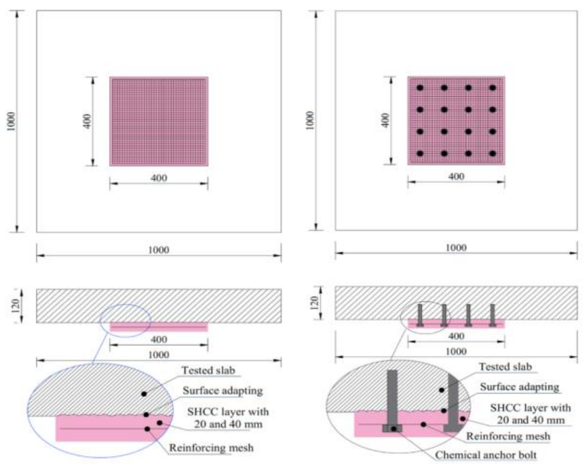

Fig. 2. Drop panels used for strengthening punching [81]

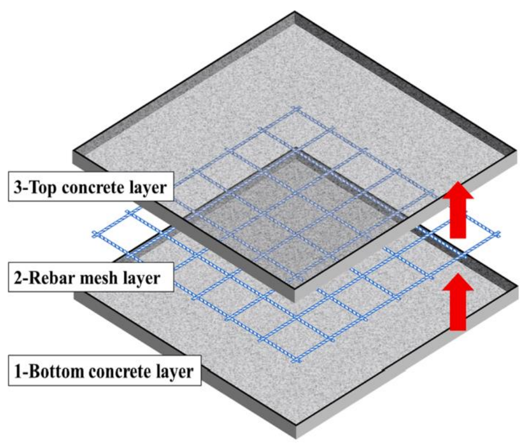

Fig. 3. Application of high-performance concretes [88].

2.2. RESULTS AND DISCUSSION FOR APPLICATION OF HPCS

The ongoing evolution in the structural rehabilitation of RC slabs has prompted numerous investigations into material innovations, strengthening techniques, and performance enhancement strategies. A comparative and critical study of eight recent papers identified here by their respective file names reveals a broad spectrum of solutions, each tackling specific failure modes such as punching shear, flexural cracking, corrosion deterioration, and blast or impact resistance. The results obtained in these studies provide a foundation for evaluating practical engineering applications and guiding future research directions. The study presented be Elsamak et al. [80] examines the use of anchored and epoxied ferrocement strips for improving the flexural performance of two-way RC slabs. The research introduces a novel method that substitutes full-layer retrofitting with strategically placed ferrocement strips in orthogonal and diagonal patterns. The experiments demonstrated that all strengthened slabs outperformed the control slab, with load-carrying capacity improvements ranging from 12% to 33%. Orthogonal arrangements outperformed diagonal ones, and anchoring the strips added another 4.1%–5.7% gain in capacity. Interestingly, the addition of a second welded steel mesh (WSM) layer brought only modest improvements (5.4%–5.9%), suggesting diminishing returns. Finite element analysis confirmed the experimental results and revealed that increasing the reinforcement ratio and anchoring length shifted the failure mode from intermediate debonding to a more desirable flexural mode. This study underscores the benefits of efficient material use and the role of anchorage in mitigating bond failure.

In the study conducted by Ghalla et al. [81]the researchers focused on mitigating punching shear failure in two-way flat slabs by incorporating drop panels made from SHCC. The key goal was to enhance the safety and sustainability of RC flat slabs that are inherently vulnerable to brittle punching failure [80,87]. The introduction of SHCC drop panels—further reinforced with either GFRP or galvanized steel mesh (GSM) yielded notable improvements in stiffness, crack control, and energy absorption. Slabs with GSM performed better than those with GFRP, particularly in stiffness (up to 237% increase) and energy absorption (up to 249%). Anchor bolts further enhanced performance regardless of panel thickness, with increased numbers of anchors correlating positively with load-bearing capacity. The most significant gains were observed with 16 anchor bolts, showing a 53.5% increase in ultimate load capacity. This study provides compelling evidence for the effectiveness of SHCC-based drop panels as a mitigation technique for punching shear, offering both mechanical and durability advantages.

A study prepared to assess the punching performance [84] offers a combined system involving CFRP rods embedded in an UHPFRC jacket, enhanced by a mechanical anchorage system (MAS). This strengthening method was tested under cyclic loads to simulate real structural behavior. The experiments compared three slab configurations: a control slab, a slab with UHPFRC jacket only, and one with CFRP rods integrated within the UHPFRC. Results showed an 82% increase in ultimate load capacity for the fully reinforced slab. The MAS played a vital role in preventing premature debonding, a common failure mode in externally bonded systems. This hybrid technique effectively improved both the flexural and ductile response, illustrating how multi-material integration can overcome limitations of individual components as studied previously [85–87,89]. Moreover, numerical simulations aligned well with experimental observations, reinforcing confidence in predictive models for such complex systems. The focus shifts to bridge slabs constructed with UHPR$_u$C, cast using SIP glass fiber-reinforced polymer (GFRP) formwork [85]. The slabs were designed with special stiffeners—either square hollow sections or Y-shaped—to enhance shear resistance. A critical finding was that the inclusion of 20% crumb rubber improved damping by 1.5 times and strain capacity by 3.5 times over reference slabs. The Y-shaped stiffeners significantly enhanced shear strength and ultimate load, especially when combined with the GFRP SIP formwork. The improved damping behavior and energy absorption from rubber content presents a dual benefit: structural enhancement and sustainability through recycled materials. The study also revealed that experimental results closely matched theoretical predictions for square stiffeners, but the Y-shaped configurations exceeded predictions by 44%, indicating a need for refined modeling techniques to account for complex geometries.

A notable deviation from the other studies, [86] explores the effect of post-strengthening corrosion on RC slabs retrofitted with textile-reinforced strain-hardening cementitious composites (TR-SHCC). The paper evaluated EB and NSE TR-SHCC strengthening strategies under accelerated corrosion. Results indicated that EB systems lost much of their effectiveness after prolonged corrosion exposure, with a near-total loss of load capacity by 30 days. In contrast, NSE systems particularly those with full SHCC cover replacement—retained superior performance and resisted corrosion-induced degradation. The use of SHCC in this context proves advantageous due to its crack-bridging capability and corrosion resistance. A prediction model for ultimate moment capacity of corroded slabs was proposed and validated against test results, offering a practical design tool. This study is particularly relevant in aggressive environments where corrosion is inevitable and maintenance access is limited.

The field-scale research [87] evaluated the flexural behavior of hollow slab girders strengthened on the compression zone using UHPC. Four-point bending tests and finite element simulations were used to assess performance. The strengthened girders demonstrated increases of 11.5% in cracking load and 23.7% in ultimate load. Unlike most studies that focus on the tension side, this work emphasized compression zone rehabilitation an area often neglected. The study found that increased UHPC thickness and prestress notably improved ductility and stiffness, though prestress had limited influence on ultimate strength. By testing on full-scale field components, the research offers rare insights into real-world applications and supports the adoption of UHPC overlays in aged infrastructure. The integration of analytical formulas for cracking and ultimate loads further bolsters the study's practical utility. The investigation [88] addressed the use of 630 MPa high-strength rebar (T63) and UHPC in enhancing blast resistance of RC slabs under contact explosions. Five slab specimens were tested under varying explosive loads. The results showed that T63-reinforced slabs exhibited lower damage levels, smaller crater depths, and reduced rear-side spalling compared to conventional HRB400 reinforcement. When combined with UHPC, the slabs resisted perforation even under high-intensity loads, whereas HRB400 slabs failed catastrophically. Dynamic stress-strain responses confirmed superior energy dissipation and peak acceleration reduction. The study's computational models revealed that existing empirical methods underestimate the performance of UHPC and high-strength steel-reinforced slabs under blast loading. This research contributes significantly to civil defense design, proving the feasibility of advanced materials in withstanding extreme dynamic events.

Finally, [93] used numerical modeling to evaluate the high-velocity projectile impact (HVPI) resistance of RC slabs strengthened with UHPC. The finite element analysis explored various slab configurations and identified that placing a UHPC layer directly on the impact face without embedded steel yielded the best performance. Increased UHPC thickness reduced projectile residual velocity, delaying or preventing perforation. The study examined several variables including projectile shape, mass, and striking velocity. Empirical formulas were derived to estimate the ballistic limit of the system. This research is crucial for protective structures in military and critical infrastructure applications. It emphasizes the strategic use of UHPC in hostile environments and provides a validated modeling approach for future design.

In conclusion, the reviewed studies each present significant strides in the field of RC slab strengthening, highlighting both established and novel methods. Ferrocement, SHCC, CFRP, UHPFRC, and TR-SHCC all offer unique benefits depending on the performance objective be it flexural capacity, durability, blast resistance, or corrosion mitigation. Mechanical anchorage and hybrid systems prove especially effective in preventing premature debonding, a common limitation in externally bonded techniques. Furthermore, the integration of finite element modeling with experimental validation enhances the reliability of predictive tools, aiding in design optimization. Collectively, these investigations underscore the versatility of high-performance composites and advanced reinforcement systems in addressing the multifaceted challenges of concrete slab deterioration and structural resilience.

3. DATABASE FOR PREVIOUS STUDIES FOR SUSTAINABLE MATERIALS

3.1. APPLICATION OF SUSTAINABLE MATERIALS

Walid Mansour et al. [82] investigated methods for enhancing the punching capacity of two-way RC flat slabs using aluminum sheets as external reinforcement (Fig. 4). The study included nine RC slabs measuring 1000 mm × 1000 mm × 120 mm, with one unstrengthened control slab and eight strengthened specimens. The key parameters studied were aluminum sheet thickness (0.6, 0.8, 1.0, and 1.2 mm) as shown in Table 2 and sheet orientation (vertical-horizontal vs. diagonal at 45°). The slabs were tested using centered loading on a 100 mm × 100 mm steel plate, and deflections were recorded with linear variable differential transformers (LVDTs). Results indicated that vertical-horizontal configurations exhibited superior stiffness and punching resistance, with 1.2 mm thick sheets improving ultimate load by 71%. Additionally, an analytical model was proposed to predict slab punching capacity based on aluminum thickness and configuration, highlighting aluminum sheets as an efficient strengthening method.

Ghalla et al. [83] conducted an experimental and numerical study to enhance the punching performance of two-way RC flat slabs by embedding aluminum sections internally. The study involved ten quarter-scale slab specimens—one control and nine strengthened—tested under central loading. The slabs measured 1000×1000×120 mm and were reinforced identically. Three reinforcement configurations (orthogonal, diagonal, and hybrid) and three aluminum thicknesses (1.0, 1.5, 2.0 mm) as shown in Table 2were tested. Each slab had eight aluminum sections. The specimens were cast with concrete of 25.1 MPa compressive strength, tested after 28 days. A load cell and LVDTs measured central deflection during punching tests. Results showed that orthogonally reinforced slabs achieved the highest gains in stiffness, absorbed energy, and ultimate load (up to 68.9% increase over the control) as shown in Fig. 5. A finite element model using ABAQUS was also developed and validated to study the effect of aluminum spacing. This model confirmed the experimental outcomes.

Ashteyat et al. [90] investigated a novel repair method for high-strength concrete two-way slabs damaged by elevated temperatures using NSM-CFRP ropes as shown in Fig. 6. The study involved eight slabs (1050×1050×70 mm) as shown in Table 2, including two normal-strength and six high-strength concrete slabs, tested after exposure to 600 °C for 3 hours. Variables included the number (2 or 3) and configuration (radial star or concentric square, with angles 0° or 45°) of CFRP ropes. The slabs were tested under central static loading using a hydraulic press (700 kN capacity), and deflections were monitored with LVDTs. Results showed load capacity improvements of 12% to 35%, stiffness gains of 260% to 343%, and ductility enhancements of 127% to 324% over unstrengthened slabs. Configurations R-SR and 3R-CS 45° achieved the best performance, even surpassing original (undamaged) slab capacity by up to 10%, demonstrating NSM-CFRP's viability as a repair strategy.

Golham [91] studied the flexural behavior of one-way concrete slabs with mid-span openings, reinforced with GFRP bars and strengthened using CFRP sheets. The experimental program tested five slabs (2650×750×150 mm), including one solid slab as a control. Two slabs had either a rectangular (250×500 mm) as shown in Table 2 or two square (250×250 mm) openings without strengthening, and two similar slabs were strengthened with CFRP sheets. All slabs were reinforced with GFRP bars and tested under two-point loading until failure. Deflection and strain were measured using LVDTs and strain gauges. Results showed that openings reduced load capacity by up to 43%, while CFRP strengthening recovered 44%–52% of the lost capacity, improved stiffness by 95%–101%, and reduced deflection by 54%–56%. All slabs failed by concrete crushing. A validated finite element model in ABAQUS confirmed the experimental results and enabled parametric studies.

Mercimek [92] investigated the effectiveness of three strengthening methods—shear stud, TRM, and CFRP for reinforced concrete flat slabs with multiple openings under punching loads. A total of 38 two-way slab specimens, each 2000×2000×120 mm, were produced and tested in four series: one unstrengthened reference group and three groups strengthened by each method. Openings of 300×300, 500×500, and 700×700 mm as shown in Table 2 were placed in parallel, diagonal, and adjacent positions relative to the column. All specimens were subjected to concentric monotonic static loading, and key performance indicators—ultimate load-carrying capacity, initial stiffness, and energy dissipation—were derived from load-displacement graphs. TRM showed the most significant improvements, followed by CFRP and shear studs. Results revealed that both the size and position of openings notably influenced performance, with adjacent openings being the most detrimental. TRM emerged as the most cost-effective and structurally beneficial method for retrofitting.

Ghayeb et al. [94] investigated the effectiveness of

CFRP sheets in enhancing the punching shear resistance of reinforced concrete flat slabs. Four two-way slab specimens (1000×1000×60 mm) as shown in Table 2 were tested: one control slab and three slabs strengthened with different CFRP configurations. The CFRP was applied externally at the slab's tension zone using epoxy adhesive. Samples were tested under centrally applied static load, and displacement was measured using LVDTs. The strengthened slabs showed notable improvements in cracking resistance, stiffness, ductility, and ultimate load capacity. The best performance was observed in the slab with the highest CFRP coverage (SS3), which achieved a 16.96% strength increase and a 73.15% improvement in ductility over the control. The study also developed an analytical model to predict punching shear capacity, which showed good agreement with experimental results and current design codes, demonstrating the reliability and efficiency of CFRP for slab strengthening.

Table 2. Studies examined application of sustainable materials in RC slabs

Study	Time of work	Dimensions		Compressive strength (MPa)	Upper reinforcement	Lower reinforcement	Strengthening martials	Testing type
		Width (mm)	Thickness (mm)					
Walid et al. [82]	2024	1000	100	25	6 D 10 / m	7 D 10 / m	Aluminum sheets	Punching
Ghalla et al. [83]	2024	1000	100	25	6 D 10 / m	7 D 10 / m	Aluminum boxes	Punching
Ashteyat et al. [90]	2025	1050	70	30	----------	12 D 16 / m	CFRP ropes	Punching
Golhamet al. [91]	2023	750	150	35	8 D 8 / m	8 D 8 / m	CFRP strips	Flexural
Mercimeket al. [92]	2024	2000	120	25.6	5 D 10 / m	6 D 10 / m	CFRP strips	Punching
Ghayeb et al. [94]	2023	1000	60	25	6 D 6 / m	6 D 6 / m	CFRP	Punching

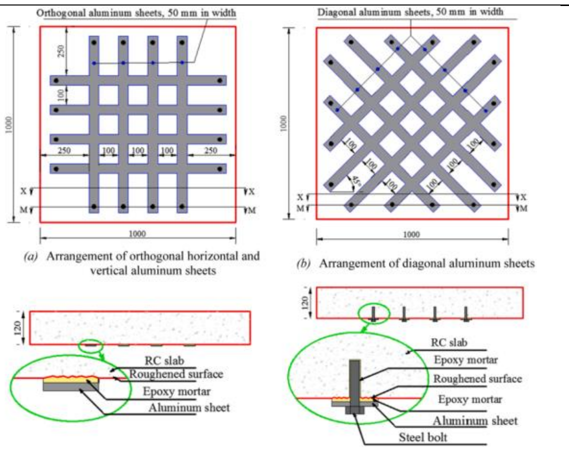

Fig. 4. Application of aluminum sheet for improve punching [82].

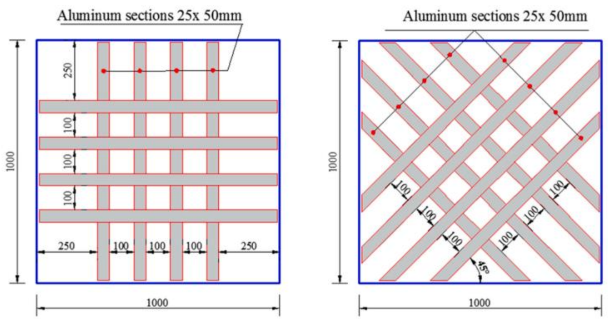

Fig. 5. Utilizing of aluminum sections for improve shear punching [83].

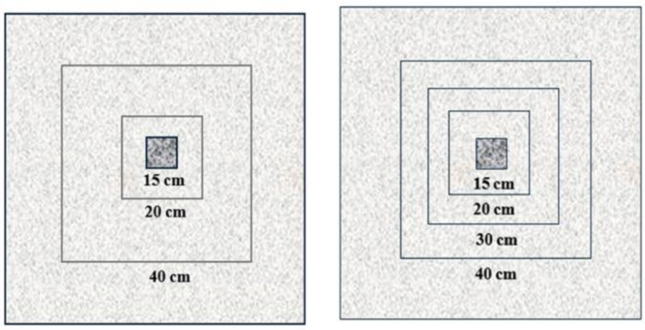

Fig. 6. Slabs tested under temperature [90]

3.2. RESULTS AND DISCUSSION FOR APPLICATION OF SUSTAINABLE MATERIALS

The research literature on RC flat slabs has seen a surge in innovative methods aimed at mitigating punching shear failure and compensating for structural deficiencies due to design flaws, thermal degradation, or functional changes. This critical analysis synthesizes findings from seven recent studies that explore a range of reinforcement strategies including aluminum sheet/section embedment, fiber-reinforced polymers, textile-reinforced mortar, and fire-resistant retrofitting solutions. Each paper contributes uniquely to advancing the performance, ductility, and resilience of concrete slabs in contemporary construction.

The study presented in [82] investigated the use of externally bonded aluminum sheets to enhance the punching capacity of two-way RC flat slabs. Nine slabs were tested with various thicknesses (0.6 to 1.2 mm) and orientations of aluminum sheets. The results conclusively demonstrated that vertical and horizontal configurations provided significantly better performance than inclined (45°) arrangements. The slab reinforced with 1.2 mm thick sheets exhibited the highest ultimate load (313 kN), stiffness (31.7 kN/mm), and energy absorption (4459 kN·mm). Importantly, as the sheet thickness increased, improvements were observed in all key performance metrics with a maximum contribution to punching capacity reaching 42%. The research further introduced a predictive analytical model that incorporates the aluminum sheet's thickness and orientation, offering a useful tool for practitioners. The work's strength lies in its clear quantitative results and practical modeling approach, although it would benefit from broader comparison with conventional strengthening materials like FRP or TRM in future studies. In [83], the authors extended the aluminum strengthening concept by embedding aluminum sections internally within the concrete matrix. Unlike external bonding, this method aims to integrate structural enhancement during the construction phase. Ten RC flat slabs were cast and tested using three reinforcement schemes: orthogonal, diagonal, and hybrid (orthogonal plus diagonal), with aluminum thicknesses of 1.0, 1.5, and 2.0 mm as shown in Table 2. The hybrid system consistently outperformed other configurations, especially with thicker sections — achieving an impressive 68.9% increase in ultimate load capacity over the control. This comprehensive study included detailed assessments of stiffness, energy absorption, and load-deflection behavior. In addition, a 3D finite element model developed using ABAQUS accurately simulated the structural response and was used to investigate spacing effects between embedded sections. The major contribution of this study is its combination of experimental validation and numerical modeling, which collectively support the effectiveness of embedded aluminum sections as a feasible alternative to traditional steel reinforcement in enhancing slab punching resistance.

The study [90] explored a specialized application: the post-fire rehabilitation of HSC two-way slabs using NSM-CFRP ropes. After exposure to 600°C for 3 hours, the slabs were retrofitted using either radial or concentric NSM rope configurations. The study highlights that even after severe thermal degradation, structural performance could be restored remarkably. Load capacity improvements ranged from 12% to 35%, stiffness gains from 260% to 343%, and ductility enhancement from 127% to 324% as shown in Table 2. The most effective schemes were the radial-star configuration with one rope and the concentric square with three ropes oriented at 45°, which nearly restored full pre-fire load capacity. The study also evaluated predictive models for punching shear, finding that empirical models like those by El-Gamal and Ospina aligned closely with test data, while ACI and JSCE-based models were either too conservative or overly optimistic. This study provides a rare but valuable contribution to structural fire engineering, suggesting that NSM-CFRP ropes are not only viable but also practical for restoring heat-damaged structures with minimal invasiveness.

The study conducted by Golham et al. [91] deals with the use of CFRP strips to strengthen GFRP reinforced slabs that include service openings. Five one-way slabs were tested under flexural loading, with both square and rectangular openings introduced at mid-span. The results underscore the detrimental effect of openings on structural behavior, reducing the failure load by 41% and 43% respectively. However, the application of CFRP strips led to significant recovery in load capacity (52% and 44%), stiffness improvement (101% and 95%), and deflection reduction at service load (56% and 54%). Notably, the strengthened slabs exhibited fewer and more controlled cracks, and all maintained integrity despite some CFRP strip failures. These results confirm the effectiveness of externally bonded CFRP in compensating for geometric discontinuities and reinforcing composite-reinforced concrete systems. The work could be expanded by exploring other geometries and loading types, but it provides solid evidence for CFRP as a go-to strengthening material in corrosion-prone environments.

The research in [92] compared three different strengthening methods for RC flat slabs with multiple openings under punching loads: shear studs, TRM, and CFRP sheets. Involving 38 specimens, the study is comprehensive in scope and examines how opening size, shape, and location affect structural performance, alongside the reinforcement technique used. TRM emerged as the most robust option, providing significant enhancements in stiffness, load capacity, and energy dissipation, without the common drawbacks of CFRP such as debonding or brittleness. For instance, slabs retrofitted with TRM or shear studs showed much higher residual capacities and improved crack patterns compared to CFRP-reinforced ones. Importantly, TRM's advantages — such as fire resistance, lower cost, and compatibility with moist surfaces make it a compelling alternative to epoxy-based systems. The study provides nuanced insight into the pros and cons of each method, emphasizing that retrofit selection must consider environmental exposure, load demands, and constructability constraints as shown in Table 2. In another hand [94] focused entirely on CFRP sheet strengthening for punching shear in RC flat slabs. Three strengthened samples and one unstrengthened control were subjected to static loading to simulate punching shear at mid-span. The findings corroborate many earlier studies: CFRP reinforcement significantly delays crack formation, increases shear resistance, and enhances both ductility and load-displacement behavior. The experimental results were further validated through analytical modeling, which proved consistent with various practical design codes. What sets this study apart is its emphasis on the potential for post-construction retrofitting in response to design changes, deterioration, or increased loads. The study also highlights limitations with epoxy use namely poor fire resistance and environmental vulnerability but affirms CFRP's high efficiency when applied in dry, controlled conditions. The discussion concludes with a call for more robust design guidance, particularly for slab-column interfaces in high-risk or retrofit-heavy projects.

The final paper in this series, [94], addresses the high-velocity impact resistance of RC slabs strengthened with UHPC layers. While not primarily focused on punching shear, the study is included due to its relevance in extreme loading scenarios such as blast or projectile impact. The simulation results show that a snugly placed UHPC layer on the impact face, without steel reinforcement, provides optimal resistance against projectile penetration. This setup maximized the projectile deceleration and minimized local damage. Parameters such as projectile nose shape, UHPC thickness, and compressive strength were explored, culminating in an empirical formula to estimate ballistic limits. Although purely numerical, the study's high-fidelity finite element model is validated against prior experimental data and provides a strong foundation for applying UHPC retrofits in military or high-security civil infrastructure. This research broadens the context of slab strengthening by addressing impacts not typically encountered in standard building design but increasingly relevant in critical facility engineering.

4. CONCLUSIONS

Fourteen studies reviewed in this analysis represent the current state of the art in RC slab strengthening research. From external and embedded aluminum reinforcements to CFRP retrofits and TRM overlays, each method offers a unique balance of mechanical improvement, durability, and constructability. Several clear patterns emerge: external strengthening methods like CFRP are effective but prone to debonding and fire sensitivity; internal methods (e.g., embedded aluminum) show excellent integration but require pre-construction planning; TRM presents an attractive hybrid with good mechanical and fire resistance properties; and advanced methods like NSM-CFRP ropes or UHPC layers open new possibilities in structural rehabilitation and protective design. Future research would benefit from standardizing comparative frameworks including load types, failure modes, cost analyses, and life-cycle performance to better guide engineers in selecting the most appropriate method for each scenario. Nevertheless, the collective findings offer a robust, evidence-based foundation for improving the safety, durability, and functionality of concrete slab systems in both new and existing structures. The reviewed studies explore a wide range of strengthening techniques for RC slabs, particularly targeting punching shear resistance, flexural enhancement, and damage mitigation under extreme conditions such as high temperatures or blast loads. Various materials and configurations were investigated, including externally bonded and embedded aluminum sheets/sections, CFRP/GFRP, TRM, SHCC, ferrocement, and UHPC. Strengthening methods were applied to slabs with service openings, corrosion-damaged areas, and thermally deteriorated zones. Experimental programs were often validated through finite element modeling, providing both empirical and analytical perspectives. Several techniques demonstrated notable improvements in load capacity (up to 68.9%), stiffness, ductility, and energy absorption, with some methods restoring or even surpassing pre-damage performance levels. Some conclusions should be highlighted:

1. Embedded aluminum sections and sheets offer significant gains in punching capacity and stiffness.
2. CFRP strengthening is effective but prone to debonding and thermal degradation.
3. TRM methods provide robust, fire-resistant, and low-cost alternatives to epoxy-based systems.
4. NSM-CFRP ropes can restore fire-damaged slabs with high efficiency and minimal disruption.
5. UHPC layers and hybrid reinforcement systems enhance impact and blast resistance.
6. Finite element modeling is crucial for optimizing and validating strengthening designs.

CREDIT AUTHOR STATEMENT

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