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Development of Low-Noise and Low-Emission Hybrid Fiber-Reinforced Rubberized Paving Concrete Mix

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Keywords
Concrete mix; Rubberized concrete Fibers; Thermal cycles; Sustainable concrete materials; Preventive maintenance.

Abstract: To address the dual concerns of environmental degradation and occupational health risks associated with emissions from traditional paving methods, this study investigates the use of Fiber-Reinforced Rubberized Concrete (FRRC) as a sustainable alternative for concrete construction. A total of 238 concrete specimens incorporating recycled rubber and different types of fibers were tested to develop eco-friendly and durable concrete materials. Key performance metrics included ultrasonic pulse velocity (UPV) and abrasion resistance, with a focus on acoustic damping, long-term durability, and maintenance efficiency. The influence of repeated thermal cycling was also evaluated to replicate real-world service conditions. The results showed that the incorporation of rubber and fibers significantly improved both UPV and abrasion resistance. Furthermore, FRRC demonstrated better performance retention after thermal exposure compared to conventional concrete, highlighting its potential for use in green infrastructure. This approach promotes the recycling of waste materials and contributes to safer working environments by reducing harmful emissions on construction sites.

1. Introduction

The increasing emphasis on environmental sustainability and quality of life has driven the widespread interest in the development and implementation of low-noise, or “quiet,” pavement concrete mix technologies. As highlighted by Donavan [1], such pavement concrete mixes play a vital role in mitigating noise pollution, particularly in urban and transportation-heavy regions. Tire–pavement concrete mix interaction noise is governed by multiple parameters, including material composition, pavement concrete mix thickness, and surface friction characteristics, as discussed by Biligiri et al. [1, 2]. Concurrently, the global community faces escalating environmental challenges arising from emissions produced

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throughout the pavement concrete mix lifecycle, with significant contributions from vehicular traffic and maintenance operations. Mukherjee and Cass [3], emphasize that these emissions are key contributors to environmental degradation and pose substantial risks to public health. Accordingly, the development of strategies aimed at reducing pavement concrete mix-related emissions, particularly during the maintenance phase, is critical. Ma et al. [4] argue that such mitigation strategies are essential to address the broader environmental impact of transportation infrastructure and to preserve ecological stability.

In the context of rigid pavement concrete mixes, the durability and long-term performance of concrete surfaces are largely influenced by their mechanical properties and resistance to surface abrasion, as noted by Kewalramani et al. and Mohamed et al. [5, 6]. The evolution of aircraft technology has introduced unprecedented mechanical demands on airport pavement concrete mixes, necessitating advanced design solutions and materials that can withstand higher loads, dynamic stresses, and surface wear. Fei et al. [7-11] underscore the need for pavement concrete mix systems to evolve in response to these increasing demands. Additionally, thermal loads from aircraft systems—specifically exhaust gases from auxiliary power units (APUs) and vectored thrust mechanisms—impose significant stress on pavement concrete mix surfaces. Benazzouk et al. [12-15] point out that these thermal exposures can compromise pavement concrete mix integrity unless properly addressed through thermally resistant materials and innovative design practices.

From an environmental perspective, when excluding embodied emissions associated with construction materials such as cement and steel, concrete pavement concrete mixes have been shown to produce lower emissions during the construction phase than flexible pavement concrete mix systems (Kumar et al. [16]). As performance expectations for airfield pavement concrete mixes continue to rise, there is a growing necessity to develop advanced concrete mixtures that not only meet structural requirements but also align with sustainability objectives. Jin et al. [17-19] highlight the importance of enhancing mechanical performance while minimizing environmental impact. Rubberized concrete (RC) has emerged as a promising material in this regard, offering notable environmental and mechanical benefits. As reported by Carroll et al. [20-28]. RC addresses global waste management concerns—particularly regarding end-of-life tires—while contributing to improved impact resistance and energy absorption. Its use in airport pavement concrete mix applications offers added advantages in terms of functional performance (Liu et al. [29]).

Despite these benefits, RC suffers from a well-documented reduction in compressive strength, which limits its use in load-bearing applications (Thomas et al. [30, 31]) suggest that fiber reinforcement, particularly using a hybrid approach, can substantially improve structural performance. Furthermore, the combined use of rubber and fibers has demonstrated potential in reducing pavement concrete mix-related noise emissions, thereby contributing to both environmental and societal well-being (Turatsinze et al. [34, 35]).

However, research indicates that single-fiber reinforcement often results in only limited improvements across a narrow spectrum of concrete properties. Abaza and Hussein [36] argue that a hybrid fiber approach—incorporating fibers of varying types and functions—

may offer a more comprehensive enhancement in performance, addressing both mechanical deficiencies and acoustic demands. In light of these considerations, this study investigates the potential of hybrid fiber-reinforced rubberized concrete as a sustainable, high-performance material for use in low-noise, low-emission airport pavement concrete mix systems.

Hybrid fiber-reinforced concrete has emerged as a promising solution in mitigating spalling damage in airfield pavement concrete mixes, as highlighted by Muhammad Hossain et al. This research underscores the material's enhanced mechanical and thermal properties, which are pivotal in the development of low-noise and low-emission paving systems [54]. At Bologna Airport, studies have demonstrated the efficacy of rubberized concrete in efficiently distributing loads, thereby reducing stress under traffic conditions, a critical attribute for the sustainable development of airport pavements —a critical attribute for the sustainable development of concrete mixes aimed at minimizing noise and emissions [55]. The lightweight and noise-isolating characteristics of rubberized concrete make it suitable for diverse applications in airport pavement concrete mixes, promoting sustainable construction practices [56]. Additionally, high-performance concrete incorporating rubber aggregates shows promise in enhancing impact resistance and durability on airport runways, essential qualities for achieving low-noise and low-emission paving systems [57].

Current advancements in concrete materials for airport pavement concrete mixes continue to evolve, driven by the imperative to enhance performance, durability, and environmental adaptability, which are crucial for future low-noise, low-emission paving systems [58]. The development of such systems using hybrid fiber-reinforced rubberized concrete involves integrating its enhanced freeze-thaw resistance, crack propagation inhibition, acoustic insulation, and thermal regulation capabilities into specialized scenarios like airport pavement concrete mixes [59]. Hybrid fiber-reinforced concrete, through the reinforcement of mechanical and thermal properties, effectively mitigates spalling damage caused by aircraft fluids, thereby increasing flexural strength and thermal conductivity, which are critical for airfield pavement concrete mixes [61]. Moreover, the environmental of rubberized concrete, including its low density and suitability for noise isolation and thermal insulation, underscore its sustainability in airport infrastructure [62]. Incorporating rubber aggregates further enhances the impact and frost resistance of concrete, ensuring durability under harsh environmental conditions typically encountered on airport runways [63].

In summary, hybrid fiber-reinforced rubberized concrete amalgamates the advantageous properties of both materials, offering improved mechanical properties, durability, and environmental adaptability. This study explores the synergistic potential of hybrid fiber-reinforced rubberized concrete in achieving sustainable solutions for airfield pavement concrete mixes. By enhancing mechanical strength, reducing maintenance-related emissions and costs, and improving acoustic performance, hybrid RC emerges as a transformative material in the pursuit of durable and environmentally responsible airport pavement concrete mixes.

2. Experimental Details

2.1. Materials

The experimental program provides a comprehensive assessment of materials, testing procedures, specimen preparation, and instrumentation. The design of both plain concrete (PC) and rubberized concrete (RC) mixes was adapted from the authors' previous research framework [37, 64, 65]. Figure 1 illustrates the constituent materials utilized in the study.

(a) **(b)** **(c)**

Fig. 1: The selected materials are (a) hooked-end steel fibers, (b) glass fibers, and (c) recycled crumb rubber **[64]**.

All concrete mixtures were proportioned to achieve targeted mechanical properties suitable for rigid pavement concrete mix applications. Specifically, the mixtures were designed to achieve a 28-day flexural strength ranging from 4.14 to 5.17 MPa and a compressive strength of approximately 30.3 MPa. These values are consistent with the specifications outlined in FAA 150/5320-6F, FAA Item P-501, and the Egyptian Civil Aviation Authority (ECAA)-EAC No. 139-11 standards [38-42]. Seventeen rubberized concrete mix variations, incorporating steel fibers (SF), glass fibers (GF), or combinations of both, were produced to investigate the influence of fiber type and dosage. The compositions and fiber dosages for all primary mix designs evaluated in this study are presented in Table 1.

Table 1: Selected contents and combinations of rubber, steel fibers, and glass fibers incorporated into PC [64].

Mix type	Mix code	SF (kg/m^3)	V_f %	GF (kg/m^3)	V_f %	Rubber (kg/m^3)	Rubber %
Plain concrete	PC	0	0	0	0	0	0
Reinforcement concrete	RC	0	0	0	0	24.85	10
Steel fiber 10	S10	10	0.13	0	0	24.85	10
Steel fiber 20	S20	20	0.26	0	0	24.85	10
Steel fiber 30	S30	30	0.38	0	0	24.85	10
Glass fiber0.5	G0.5	0	0	0.5	0.02	24.85	10
Glass fiber1.0	G1	0	0	1	0.04	24.85	10
Glass fiber1.5	G1.5	0	0	1.5	0.06	24.85	10
Steel 10 & Glass fiber 0.5	S10G0.5	10	0.13	0.5	0.02	24.85	10
Steel 10 & Glass fiber 1.0	S10G1	10	0.13	1	0.04	24.85	10

Mix type	Mix code	SF (kg/m³)	V_f %	GF (kg/m³)	V_f %	Rubber (kg/m³)	Rubber %
Steel 10 & Glass fiber 1.5	S10G1.5	10	0.13	1.5	0.06	24.85	10
Steel 20 & Glass fiber 0.5	S20G0.5	20	0.26	0.5	0.02	24.85	10
Steel 20 & Glass fiber 1.0	S20G1	20	0.26	1	0.04	24.85	10
Steel 20 & Glass fiber 1.5	S20G1.5	20	0.26	1.5	0.06	24.85	10
Steel 30 & Glass fiber 0.5	S30G0.5	30	0.38	0.5	0.02	24.85	10
Steel 30 & Glass fiber 1.0	S30G1	30	0.38	1	0.04	24.85	10
Steel 30 & Glass fiber 1.5	S30G1.5	30	0.38	1.5	0.06	24.85	10

2.2 Experimental Tests

2.2.1 Ultrasonic Pulse Velocity (UPV) test

The ultrasonic pulse velocity (UPV) test was conducted on three concrete cubes with side dimensions of 100 mm, following ECP 203 and ASTM C597. The test used direct transmission to determine pulse velocity and assess wave absorption characteristics. The acoustic properties of the concrete mixes were evaluated using this technique, consistent with methodologies reported by Biligiri and Way [43, 44]. The pulse transmission velocity (V) in the concrete was calculated using Equation (1):

$$V = L/T \tag{1}$$

Where:

- L is the transmission distance (m),
- T is the transmission time through the concrete (s), and
- V is the resulting pulse transmission velocity (m/s), as noted by Bogas **[45].**

The acoustic impedance (Z) of the concrete was subsequently determined using the estimated UPV and mix density (ρ), as expressed in Equation (2):

$$Z = \rho * v \tag{2}$$

where:

- Z is the impedance ($kg/m^2 \cdot s$),
- ρ is the density of the concrete mix (kg/m^3),
- V is the ultrasonic pulse velocity (m/s).

To further evaluate acoustic damping behavior, a damping index (DAMP) was computed as an indicator of the energy dissipation characteristics of the concrete mix material. The DAMP percentage was derived using impedance values and is expressed in Equation (3), as described by Biligiri and Way [43]:

$$DAMP\ \% = 100*(100/Z)^{0.4} \tag{3}$$

A DAMP value near 1% indicates minimal acoustic damping, whereas values approaching 100% signify high damping capacity.

Fig. 2: Ultrasonic pulse velocity for UPV test.

2.2.2.Abrasion Resistance Test

Abrasion resistance was evaluated using four concrete cubes with dimensions of 70 mm per side, per the procedures defined in TS 699 [46] and ECP269 [47]. The specimens were oven-dried and weighed in air and water to determine their densities. Abrasion resistance was quantified by measuring the depth of the abraded surface, following the guidelines outlined in ECP 269. Figure 3 illustrates the test setup and methodology used to assess the abrasion performance of the concrete mix cubes.

Fig. 3: Machine used for abrasion test.

2.2.3. Thermal Cycles Test Protocol:

A controlled thermal cycling protocol was developed to simulate the thermal stresses experienced by airfield concrete mixes exposed to exhaust from auxiliary power units (APUs). The protocol involved subjecting specimens to a total of six heating and cooling cycles. Research has shown that initial exposure to high temperatures, up to 300°C, can lead to significant strength loss in concrete specimens.[13, 48]. In this study, specimens were exposed to hot air in a laboratory oven for 30 minutes per cycle, followed by a 2-hour natural cooling period at ambient room temperature. To ensure uniform thermal loading, all surfaces of each specimen were uniformly exposed to the heating environment. The specimens underwent a total of six thermal cycles, with the first three cycles reaching a maximum temperature of 150°C and the subsequent three cycles reaching a maximum of 205°C. This temperature progression was consistent with real-world thermal gradients experienced in concrete mixes[13, 14]. The temperature increase was controlled at a heating rate of 10–20 °C per minute. The target temperatures of 150°C and 205°C were reached within approximately 7 and 10 minutes, respectively. This test protocol was designed to replicate realistic and progressive thermal exposure conditions and evaluate the resulting mechanical and durability performance of the concrete specimens.

3. Results And Discussion

3.1. Ultrasonic Pulse Velocity (UPV) Results:

Figure 4 illustrates that the acoustic damping index (DAMP) of rubberized concrete (RC) was 13.67%, showing only a marginal increase compared to plain concrete (PC), which recorded a DAMP of 13.39%. Among the RC mixes reinforced with hybrid fibers, the S30G1.5 mix demonstrated the highest DAMP value at 14.39%, indicating superior acoustic performance. RC mixes containing hybrid fibers consistently exhibited the most favorable noise reduction characteristics both before and after thermal cycling, positioning them as the quietest concrete mix materials under investigation. Figure 5 presents the density values for all mix types. While DAMP increased from 13.39% to 14.39% under the tested conditions, we treat this as an early, material-level indicator rather than a direct predictor of environmental noise reduction.

Table 2 reveals that including rubber in PC resulted in a 2.94% reduction in UPV. This reduction is attributed to the rubber particles' tendency to attenuate the transmission of ultrasonic waves, lowering wave velocity, and contributing to decreased concrete mix-generated noise. As indicated by Hesami et al. [49]. The presence of internal cavities in concrete can influence wave transmission and the volume of traffic-related noise, thus impacting the DAMP index.

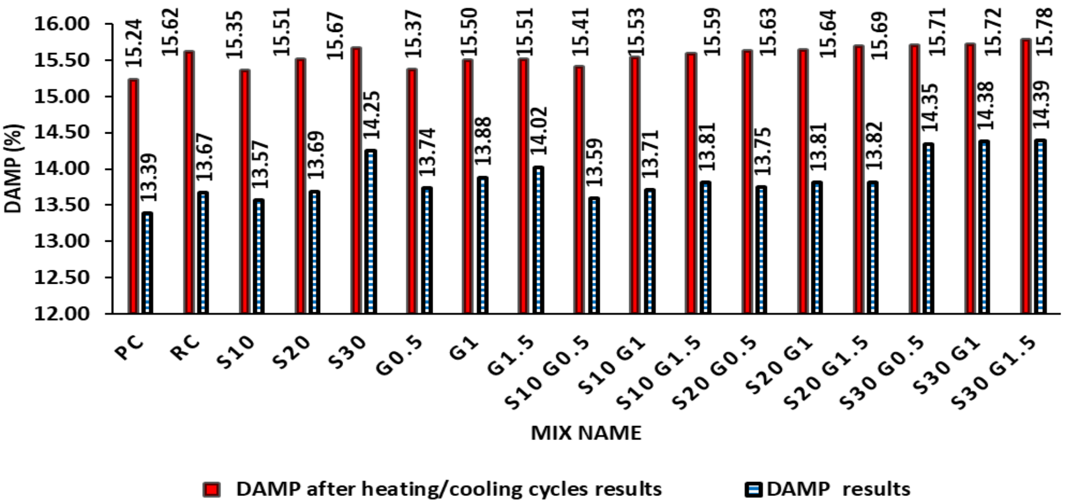


Fig. 4: Average DAMP (%) for the different concrete mix mixes.

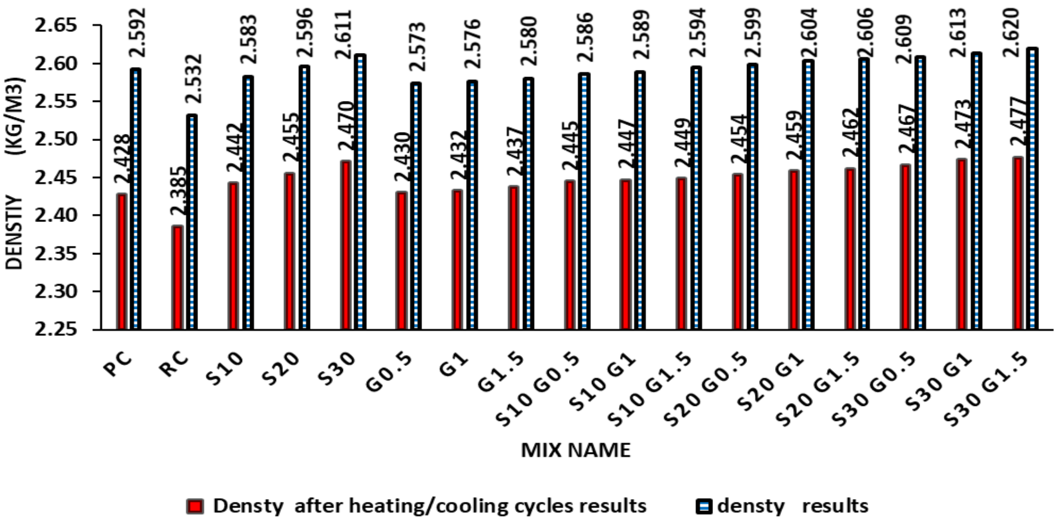


Fig. 5: Density results for all mixes.

Table 2: Loss in thickness and UPV test results

Mix code	loss in thickness (mm)		UPV	
	% ch PC*	% ch RC**	% ch PC	% ch RC
PC	0.00	6.19	0.00	2.86
RC	-6.59	0.00	-2.94	0.00
S10	-26.14	-18.34	-3.00	-0.06
S20	-44.97	-36.01	-5.88	-2.86
S30	-70.24	-59.71	-17.65	-14.29
G0.5	-9.25	-2.49	-5.88	-2.86
G1	-11.81	-4.90	-8.82	-5.71
G1.5	-20.01	-12.59	-11.76	-8.57
S10G0.5	-29.54	-21.53	-3.53	-0.57
S10G1	-33.12	-24.89	-5.88	-2.86
S10G1.5	-40.87	-32.15	-8.24	-5.14
S20G0.5	-49.43	-40.18	-7.18	-4.11
S20G1	-54.29	-44.75	-8.59	-5.49
S20G1.5	-64.43	-54.26	-8.82	-5.71
S30G0.5	-72.99	-62.29	-19.65	-16.23
S30G1	-80.63	-69.46	-20.59	-17.14
S30G1.5	-97.21	-85.01	-21.12	-17.66

* (% ch PC): Percentage change in case of PC mix is a reference.

** (% ch RC): Percentage change in case of RC mix is a reference.

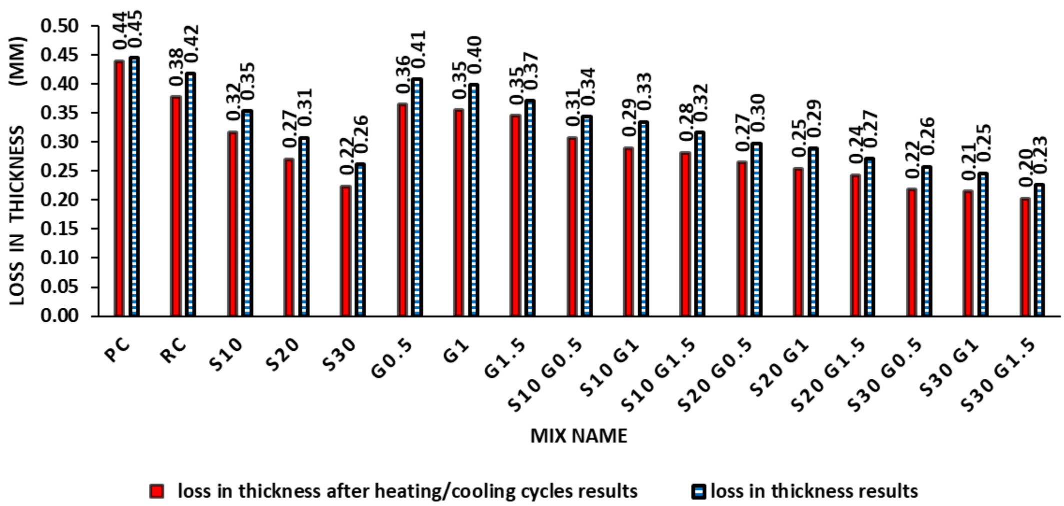


Fig. 6: Loss in thickness results for all mixes.

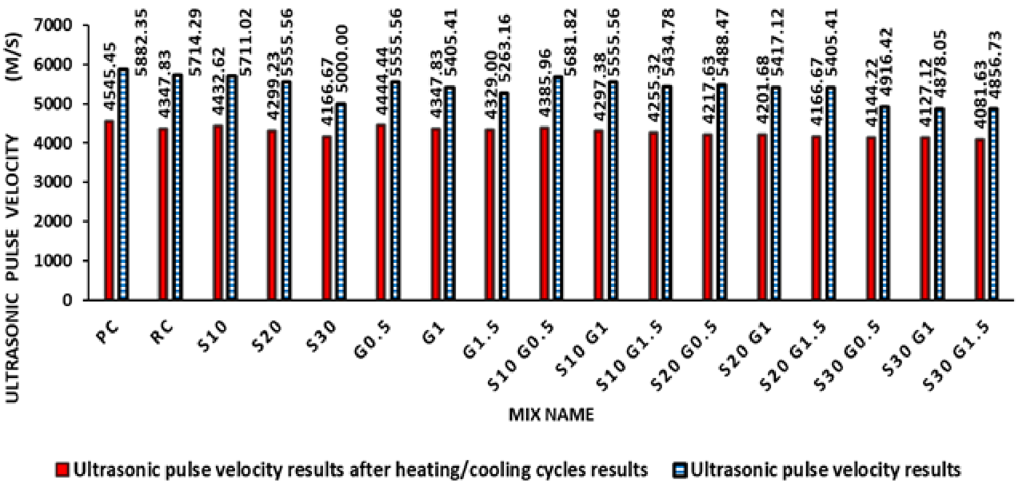


Fig. 7: UPV results for all mixes

The addition of steel fibers, glass fibers, and hybrid fibers to reinforced concrete (RC) further reduced the ultrasonic pulse velocity (UPV) by 14.29%, 8.57%, and 17.66%, respectively, as shown in Table 2 and Figure 7. These reductions are due to the heterogeneous nature of fiber-reinforced RC, where ultrasonic waves encounter multiple interfaces, resulting in partial reflection, scattering, and absorption. It is also observed that mixes with increased glass fiber content at a fixed steel fiber dosage exhibited further decreases in UPV. This behavior may be attributed to the insulating properties of E-glass fibers, which hinder ultrasonic wave propagation, as previously reported by Nik and Omran [50]. Statistical analysis of the UPV test results is summarized in Table 2, with bordered cells indicating instances where no statistically significant differences were observed compared to the control mix results.

As depicted in Figures 4 and 7, the damping (DAMP) and ultrasonic pulse velocity (UPV) values exhibited consistent trends before and after applying thermal cycles. Notably, UPV values decreased slightly post-cycling, while DAMP values increased. This behavior is primarily attributed to the formation of microvoids resulting from the partial combustion of rubber particles during heating. These voids reduce material density and continuity, leading to slower wave propagation. Consequently, the increased transmission time for ultrasonic waves corresponds to a lower UPV. These observations are consistent with previous findings by Ikpong [51]. Among all tested mixes, those incorporating steel fibers, specifically S10, S30, S30G0.5, S30G1, and S30G1.5, showed the least variation in ultrasonic pulse velocity (UPV) values after thermal exposure. This indicates that steel fiber reinforcement plays a significant role in reducing the negative effects of thermal cycling by enhancing internal structural cohesion and limiting microcrack development.

According to the classification criteria established by Solís-Carcaño et al. [52, 53], before thermal exposure, all concrete mixes qualified as "excellent" (UPV > 4575 m/s), by following thermal cycling, the mixes were classified as "good" (UPV between 4575 and 3660 m/s), reaffirming the thermal and acoustic resilience of the fiber-reinforced rubberized concrete, The percentage change in ultrasonic pulse velocity (UPV) and loss in thickness after heating/cooling cycles for all mixes is presented in Table 3.

Table 3: Percentage of change after heating/cooling cycles for all mixes

Mix code	UPV	loss in thickness
PC	-29.41	-1.28
RC	-31.43	-10.58
S10	-28.84	-11.31
S20	-29.22	-13.65
S30	-20.00	-16.91
G0.5	-25.00	-11.82
G1	-24.32	-12.20
G1.5	-21.58	-7.52
S10G0.5	-29.55	-11.71
S10G1	-29.28	-15.59
S10G1.5	-27.72	-12.14
S20G0.5	-30.13	-12.43
S20G1	-28.93	-13.37
S20G1.5	-29.73	-11.64
S30G0.5	-18.63	-18.16
S30G1	-18.20	-14.92
S30G1.5	-18.99	-11.44

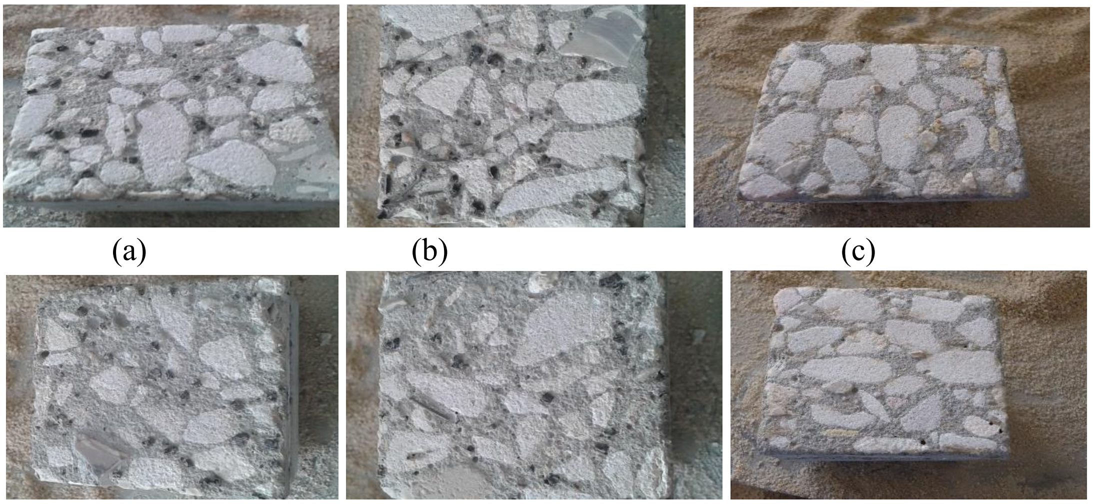
3.2. Abrasion Resistance Results:

Table 2 and Figure 6 reveal that including rubber in plain concrete (PC) led to a marginal reduction in surface wear, with a decrease in thickness loss of approximately 0.44%. This minor improvement is likely due to the elastic nature of rubber, which is more resilient under stress than traditional stone aggregates. The rubber's ability to maintain elasticity over time and its resistance to dislodgement during abrasion contributed to the increased wear resistance. These observations are consistent with the findings of Ristić [5].

Further enhancements were observed in rubberized concrete (RC) reinforced with fibers. The loss in thickness was significantly reduced by 59.71% with the addition of steel fibers, by 12.59% with the addition of glass fibers, and by 85.01% with the addition of hybrid fibers. The RC mixes with hybrid fibers exhibited the highest abrasion resistance among these. This performance is attributed to the fibers' ability to form strong interfacial bonds with the cement matrix, thereby minimizing material detachment under mechanical abrasion.

Enhanced abrasion resistance translates into practical advantages such as reduced tire–concrete mix friction noise, improved ride comfort, and greater fuel efficiency. These benefits contribute to lower maintenance demands and reduced vehicular emissions, aligning with the objectives of sustainable concrete mix design.

The abrasion resistance trends remained consistent before and after exposure to thermal cycles. However, the results after the cycles showed a slight improvement in resistance, which could be attributed to the densification of the microstructure or continued hydration caused by the thermal effects. This is supported by the data in Table 3, which shows the corresponding percentage changes. Visual analysis in Figure 8 also confirms this, as it shows no noticeable differences between the pre- and post-cycle abrasion surfaces.



(a) (b) (c)

(d) (e) (f)

Fig. 8: Post-abrasion-test images for: (a) RC with glass fiber, (b), RC with steel fibers, (c) Plain concrete, (d) RC with glass fiber after heating/cooling cycles, (e) RC with hybrid fiber after heating/cooling cycles, (f) Plain concrete after heating/cooling cycles.

4. Conclusions

This study confirms the potential of incorporating recycled rubber waste into concrete as a sustainable strategy to mitigate environmental pollution. The utilization of rubber not only contributes to environmental protection but also enhances several performance characteristics of concrete.

- The data show that rubberized concrete (RC) reinforced with hybrid fibers has the most favorable acoustic properties. It is the quietest concrete mix material both before and after being exposed to thermal cycles. The even distribution of rubber granules within the concrete helps prevent them from being dislodged, which in turn reduces surface abrasion by protecting the cement paste and aggregate. As a result, RC has significantly improved wear resistance.
- The inclusion of hybrid fibers slightly improved the durability of concrete mix surfaces and marginal structures, providing a denser and more durable surface than plain concrete or fiber-free RC. All concrete mixes tested in this study were classified as "excellent" (UPV > 4575 m/s) before thermal cycling and "good" (4575 > UPV > 3660 m/s) after cycling, based on ultrasonic pulse velocity (UPV) evaluations.
- Although all concrete mixes experienced degradation in UPV and electrical resistivity following thermal cycling, the inclusion of fibers, especially in hybrid configurations, helped mitigate these negative impacts. Increased fiber dosage correlated with slightly improved post-cycling performance retention.
- The study demonstrates that rubberized concrete with fibers, particularly hybrid fibers, exhibits enhanced abrasion resistance. This is due to the strong bonding between fibers and the cement matrix, reducing the material loss under abrasive forces.
- This improvement offers practical advantages for concrete mixes, including reduced tire noise, smoother rides, and increased fuel efficiency. It also leads to lower maintenance costs and reduced emissions, promoting sustainability.

Based on the findings, ductile rubberized concrete incorporating hybrid fibers can be considered a viable structural material for airfield concrete mixes. It offers slight advantages in noise reduction, abrasion resistance, and environmental sustainability. Ultimately, integrating hybrid fibers into rubberized concrete represents a promising advancement in green concrete technology and provides a multifaceted solution for enhancing the performance and longevity of rigid concrete mix systems, including applications such as in-concrete mix snow melting.

References

1. Donavan, P.R., "Foreword to the special issue on tire/pavement nois",. *Noise Control Engineering Journal*, vol. 57, **2009**.
2. Biligiri, K.P. *et al.*, "Evaluation of asphalt mixtures' viscoelastic properties using phase angle relationships", *International Journal of Pavement Engineering*, vol. 11, **2010.**
3. Mukherjee, A.*et al.*, "Project emissions estimator: implementation of a project-based framework for monitoring the greenhouse gas emissions of pavement. *Transportation research record,* vol. 2283, **2012**.
4. Ma, F., *et al.*, "Life cycle assessment of greenhouse gas emissions from asphalt pavement maintenance: A case study in China. *Journal of Cleaner Production*, vol. 288, **2021**.
5. Ristić, N., G. *et al.*, "Abrasion resistance of concrete made with micro fibers and recycled granulated rubber. *Zaštita materijala*, vol. 56, **2015**.
6. Kewalramani, M.A., *et al.*, "Engineered cementitious composites for modern civil engineering structures in hot arid coastal climatic conditions. *Procedia Engineering*, vol. 180, **2017**.
7. Lok, T. *et al.*, "Impact resistance and ductility of steel fibre reinforced concrete panels. *HKIE Transactions*, vol. 3, **1996**.
8. JUN, W., "Development of advanced pavement materials system for blast load. 2012.
9. YWE, O., Testing of New Composite Pavement Material for Runway B. Eng Dissertation, National University of Singapore, **2008**.
10. Ali, S., *et al.*, "Numerical study on the surface depression of the concrete runway pavement under impact load. *International Journal of Research in Civil Engineering, Architecture & Design*, vol. 4, **2016**.
11. Fei, D., *et al.*, "Mechanical response of typical cement concrete pavements under impact loading. *Mathematical Problems in Engineering*, **2017**.
12. Benazzouk, A., *et al.*, "Durability of cement-rubber composites under freeze thaw cycles. in Proceedings of International congress of Sustainable Concrete Construction, Dundee-Scotland. **2002**.
13. Bier, T.A., *et al.*, "A mechanistic study of failure of concrete subjected to cyclic thermal loads. CEMCOM RESEARCH ASSOCIATES INC LANHAM MD, **1991**.
14. Panchmatia, P., *et al.*, "Influence of mixture composition on thermal properties of concrete and the performance of rigid pavement. *Roads and Bridges-Drogi i Mosty*, vol. 13, **2014**.
15. Kordina, K., *et al.*, "Analysis of the developing damage of concrete due to heating and cooling. *Special Publication*, vol. 92, **1986**.
16. KUMAR, B., *et al.*, "Development of Methodology for Quantification of GHG Emission During Construction of Flexible and Rigid Pavement: *A Case Study. Indian Highways*, **2020**.
17. Khayat, K.H. *et al.*, "Design and Performance of Cost-Effective Ultra High Performance Concrete for Bridge Deck Overlays. Missouri. Dept. of Transportation. Construction and Materials Division, **2018**.
18. Jin, L., *et al.*, "Experimental investigation on static and dynamic mechanical properties of steel fiber reinforced ultra-high-strength concretes. *Construction and Building Materials*, vol. 178, **2018**.

19. Gunasekaran, M., *et al.*, "Impact Response and Strength Reliability of Green High Performance Fibre Reinforced Concrete Subjected to Freeze-thaw Cycles in NaCl Solution. *Materials Science*, vol. 23, **2017**.
20. Abaza, O.A., *et al.*, "Flexural behavior of steel fiber-reinforced rubberized concrete. *Journal of Materials in Civil Engineering*, vol. 28, **2015**.
21. *Carroll, J.C., et al., "Fresh and hardened properties of fiber-reinforced rubber concrete. Journal of Materials in Civil Engineering*, vol. 28, **2016**.
22. Noaman, A.T., *et al.*, "Experimental investigation on compression toughness of rubberized steel fibre concrete. *Construction and Building Materials*, vol. 115, **2016**.
23. Li, G., *et al.*, "Development of waste tire modified concrete. *Cement and Concrete Research*, vol. 34, **2004**.
24. Li, G., *et al.*, "Waste tire fiber modified concrete. *Composites Part B: Engineering*, vol. 35, **2004**.
25. Ganjian, E., *et al.*, "Scrap-tyre-rubber replacement for aggregate and filler in concrete. *Construction and building materials*, vol. 23, **2009**.
26. Moustafa, A. a*et al.*, "Mechanical properties of high strength concrete with scrap tire rubber. *Construction and Building Materials*, vol. 93, **2015**.
27. ISMAIL, A., *et al.*, "The Influence of Scrap Tire particles on Rigid Pavements characteristics (Review study). in Proceedings of the 9th International Conference of Eastern Asia Society for Transportation Studies, **2011**.
28. Association, R.M., "US scrap tire management summary. Washington, DC: Rubber Manufacturers Association, **2014**.
29. Li, Y.R., *et al.*, "Experimental and Economic Analysis of Airport Crumb Rubber Concrete (CRC) Pavement. *Advanced Materials Research*, vol. 250-253, **2011**.
30. Thomas, B.S., *et al.*, "Strength, abrasion and permeation characteristics of cement concrete containing discarded rubber fine aggregates. *Construction and Building Materials*, vol. 59, **2014**.
31. Thomas, B.S., *et al.*, "Experimental and modelling studies on high strength concrete containing waste tire rubber. *Sustainable Cities and Society*, vol. 19, **2015**.
32. Fu, C., *et al.*, "Evolution of mechanical properties of steel fiber-reinforced rubberized concrete (FR-RC). *Composites Part B: Engineering*, vol. 160, **2019**.
33. Xie, J., *et al.*, "Effects of the addition of silica fume and rubber particles on the compressive behaviour of recycled aggregate concrete with steel fibres. *Journal of Cleaner Production*, vol. 197, **2018**.
34. Turatsinze, A., *et al.*, "Positive synergy between steel-fibres and rubber aggregates: Effect on the resistance of cement-based mortars to shrinkage cracking. *Cement and Concrete Research*, vol. 36, **2006**.
35. Turatsinze, A., *et al.*, "Mechanical characterisation of cement-based mortar incorporating rubber aggregates from recycled worn tyres. *Building and Environment*, vol. 40, **2005**.
36. Abaza, O.A., *et al.*, "Flexural Behavior of Steel Fiber-Reinforced Rubberized Concrete. *Journal of Materials in Civil Engineering*, vol. 28, **2016**.
37. Abdullah A.S.M., *et al.*, "Investigation on Improving Rigid Pavement Properties by Adding Recycled Rubber, *Journal of Engineering Sciences*, Assuit University, Egypt. vol. 41, 2018.
38. (ECAA), E.C.A.A., EAC No. 139-11. **2012**: Egypt.
39. FAA, "Item P-501 Portland Cement Concrete (PCC) Pavement. **2016**.

40. Prassianakis, I. *et al.*, "Mechanical properties of old concrete using destructive and ultrasonic non-destructive testing methods. *Magazine of Concrete Research*, vol. 55, **2003**.
41. Frentress, D.P. *et al.*, "Harrington, Guide for partial-depth repair of concrete pavements. Iowa State University Institute for Transportation, **2012**.
42. Roesler, J., *et al.*, "Fracture behavior of full-scale, fiber-reinforced concrete slabs. Report prepared for WR Grace, Inc., University of Illinois, Urbana, IL, **2003**.
43. Biligiri, K.P. *et al.*, "Way, Noise-damping characteristics of different pavement surface wearing courses. *Road Materials and Pavement Design*, vol. 15, **2014**.
44. Biligiri, K.P. *et al.*, "Prediction of pavement materials' impedance using ultrasonic pulse velocity. Road materials and pavement design, vol. 10, **2009**.
45. Bogas, J., "Characterization of structural lightweight expanded clay aggregate concrete. Technical University of Lisbon, **2011**.
46. 699 T., "Methods of testing for natural building stones, Turkish Standards Institute: Ankara, Turkey, **2000**.
47. 269., E.c., "The Egyptian Code for Design and Construction of Concrete Structures. Housing and building research center: Giza, Egypt, **1962**.
48. Campbell-Allen, D. *et al.*, "The influence of aggregate on the behaviour of concrete at elevated temperatures. *Nuclear Engineering and Design*, vol. 6, **1967**.
49. Hesami, S., *et al.*, "Mechanical behavior of self-compacting concrete pavements incorporating recycled tire rubber crumb and reinforced with polypropylene fiber. J*ournal of Cleaner Production,* vol. 133, **2016**.
50. Nik, A.S., *et al.*, "Estimation of compressive strength of self-compacted concrete with fibers consisting nano-SiO2 using ultrasonic pulse velocity. *Construction and Building Materials*, vol. 44, **2013**.
51. Ikpong, A., "The relationship between the strength and non-destructive parameters of rice husk ash concrete. *Cement and Concrete Research*, vol. 23, **1993**.
52. Malhotra, V.M., "Testing hardened concrete: nondestructive methods, Iowa State Press, **1967**.
53. Solis-Carcaño, R. *et al.*, "Evaluation of concrete made with crushed limestone aggregate based on ultrasonic pulse velocity. *Construction and Building Materials*, vol. 22, **2008**.
54. Vairagade V., *et al.*, "Hybrid fibre reinforced concrete – A state of the art review. *Hybrid Advances*, vol. 3, **2023**. https://doi.org/10.1016/j.hybadv.2023.100035
55. Pham P., *et al.*, "Application of rubberized cement-based composites in pavements: Suitability and considerations. *Construction and Building Materials*, vol. 223, **2019**. https://doi.org/10.1016/j.conbuildmat.2019.08.007.
56. Tran T., *et al.*, "Brand A. A comprehensive review on treatment methods for end-of-life tire rubber used for rubberized cementitious materials. *Construction and Building Materials*, vol. 359, **2022**. https://doi.org/10.1016/j.conbuildmat.2022.129365
57. Wu Y., *et al.*, "Kong Y. Drop hammer impact tests of airport pavement slabs composed of modified rubber aggregate concrete. *Construction and Building Materials*, vol. 458, **2025**. https://doi.org/10.1016/j.conbuildmat.2024.139519
58. Li M., *et al.*, "A state-of-the-art assessment in developing advanced concrete materials for airport pavements with improved performance and durability. *Case Studies in Construction Materials*, vol. 21, **2025**. https://doi.org/10.1016/j.cscm.2024.e03774
59. Xingyu Zhao, *et al.*, "Influence of aluminum enrichment zone on chloride ion penetration resistance in rubber cement-based materials, *Construction and Building Materials*, vol. 471, **2025**, https://doi.org/10.1016/j.conbuildmat.2025.140619

60. Phuong Ngoc Pham, *et al.*, "Anaclet Turatsinze, Ahmed Toumi, Rafat Siddique, Application of rubberized cement-based composites in pavements: Suitability and considerations, *Construction and Building Materials*, vol. 223, **2019**, https://doi.org/10.1016/j.conbuildmat.2019.08.007
61. Vikrant S. Vairagade, *et al.*, "Dhale, Hybrid fibre reinforced concrete – A state of the art review, *Hybrid Advances*, vol. 3, **2023**, https://doi.org/10.1016/j.hybadv.2023.100035
62. Thien Q. Tran, *et al.*, "A comprehensive review on treatment methods for end-of-life tire rubber used for rubberized cementitious materials, *Construction and Building Materials*, vol. 359, **2022**, https://doi.org/10.1016/j.conbuildmat.2022.129365
63. Ying Wu, *et al.*, "Drop hammer impact tests of airport pavement slabs composed of modified rubber aggregate concrete, *Construction and Building Materials*, vol. 458, **2025**, https://doi.org/10.1016/j.conbuildmat.2024.139519
64. Zainab I. Abd Elshafy; *et al.*, "Thermo-Mechanical Properties Evaluation of Fiber-Reinforced Rubberized Concrete Mixes for Airfield Pavements". *JES. Journal of Engineering Sciences*, vol. 53, **2025**. doi: https://doi.org/10.21608/jesaun.2025.389293.1531
65. Al Sayed M. Abdullah; *et al.*, "INVESTIGATION ON IMPROVING RIGID PAVEMENT PROPERTIES BY ADDING RECYCLED RUBBER". *JES. Journal of Engineering Sciences*, vol. 46, **2018**. doi: https://doi.org/10.21608/jesaun.2018.110139