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Experimental study on flexural performance of rubber coagulation

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Abstract The disposal of discarded rubber tires poses significant environmental challenges, including resource depletion and ecological damage. To address these issues and enhance the sustainability of construction materials, the potential application of rubberized concrete in airport pavement engineering is explored. In this study, rubber particles sized 3-5 mm, 6-10 mm, and rubber fibers sized 10-20 mm were incorporated into concrete by substituting sand at volumetric replacement levels of 5%, 10%, 15%, and 20%. Through four-point bending tests, the influence of rubber morphology and replacement levels on the flexural strength and flexural elastic modulus of rubberized concrete was systematically evaluated. Experimental results indicate that higher rubber replacement levels lead to a gradual reduction in flexural strength and elastic modulus. At a 20% replacement level, the flexural strength of concrete with 3-5 mm particles, 6-10 mm particles, and 10-20 mm fibers decreased by 13.5%, 15.6%, and 20.5%, respectively, while the corresponding elastic modulus declined by 20.3%, 18.5%, and 20.9%. Notably, concrete with 3-5 mm rubber particles exhibited the highest flexural strength, while concrete with 10-20 mm rubber fibers showed the lowest elastic modulus. These findings suggest that a rubber replacement level below 10% can optimize mechanical properties while minimizing reductions in strength, highlighting the potential of rubberized concrete for use in airport pavement engineering.

Index Terms Rubberized Concrete, Rubber morphology, Rubber replacement level, Flexural strength, Flexural elastic modulus

I. Introduction

Airport runways, serving as the primary platform for aircraft takeoff and landing, are critical components of airfield infrastructure and play a pivotal role in a nation's transportation network. Cement concrete pavements, widely utilized in domestic airports due to their superior rigidity, load-bearing capacity, and extended design lifespan compared to asphalt concrete, directly influence the efficiency of airport operations, including takeoff frequency and passenger throughput [1]. During aircraft operation, airport pavement slabs experience substantial vertical pressure and bending stresses from wheel loads. As the flexural strength of cement concrete is inherently lower than its compressive strength, it becomes a key parameter for ensuring the structural performance of airport pavements [2], [3]. With the advent of larger aircraft, the imposed loads on airport pavements have escalated, necessitating improvements in the strength and load-bearing capacity of cement concrete pavements. However, an increase in flexural strength is typically accompanied by a rise in flexural elastic modulus, which can compromise operational comfort for aircraft and induce internal thermal stresses within the pavement, ultimately affecting its long-term durability and performance [4], [5]. Consequently, the demand for innovative pavement materials with a balance of high strength and low elastic modulus has become increasingly critical.

The disposal of waste tires has become a pressing global issue, significantly impacting both natural resources and the environment. Conventional methods of handling discarded tires, such as landfilling or incineration, pose serious ecological risks, including soil contamination, air pollution, and greenhouse gas emissions [6]. As a potential solution, rubberized concrete emerges as an innovative composite material in which waste rubber is incorporated as a partial aggregate replacement. This material not only addresses global rubber waste pollution but also enhances concrete properties, such as crack resistance, energy absorption, and flexibility [7], [8]. Extensive research has been conducted to evaluate the mechanical properties of rubberized concrete. For instance, Wang et al. [9] found that replacing 10%, 20%, 30%, and 40% of sand with rubber particles (4.75 mm) increased slump, cumulative bleeding, and setting time. Nasir N. A. M. et al. [10] observed a 13% reduction in compressive strength at a 10% replacement level. Similarly, Aslani and Khan [11] reported that larger rubber particle sizes result in significant compressive strength losses. Gisbert [12] demonstrated that replacing sand with rubber at levels of 10% to 40% reduced Young's modulus by up to 91% for coarse particles and 97.77% for fine particles. Furthermore, Liu

[13] showed that rubber incorporation improved peak deflection and residual strength by 61.5% and 128.8%, respectively, in steel fiber rubberized concrete. Abdelmonem et al. [14] concluded that while flexural strength decreases significantly with rubber content, this decline stabilizes beyond a 20% replacement level. These findings collectively highlight the potential and limitations of rubberized concrete, paving the way for further exploration in specialized applications such as airport pavements.

Although substantial research has been conducted on rubberized concrete as an innovative material, most studies have primarily focused on its application in plastic concrete for construction engineering. In contrast, the performance of dry-mix concrete, which is widely used in airport pavement, has not been systematically or comprehensively investigated in the context of rubber incorporation. While significant progress has been made in incorporating rubber into conventional materials such as natural sand for various applications, including airport pavements and other infrastructure [15]-[18], critical issues such as determining the optimal rubber morphology and dosage for cement-based dry-mix concrete remain unresolved. These gaps are particularly pressing given the stringent performance demands of airport pavements, where materials must balance strength and flexibility to withstand high loads and minimize cracking [19]. The ability of rubberized concrete to meet these engineering requirements therefore requires further exploration. This study aims to address these gaps by examining the flexural strength and flexural elastic modulus of rubberized concrete, providing valuable scientific insights for its potential application in airport runway engineering.

The remainder of this study is structured as follows: Section 2 outlines the materials and mix design, including rubber types and replacement levels. Section 3 describes the experimental procedures for testing consistency, compressive strength, flexural strength, and elastic modulus. Section 4 presents and analyzes the results, focusing on the influence of rubber morphology and replacement levels. Finally, Section 5 summarizes key findings and offers recommendations for future research and airport pavement applications.

II. Materials and Mix design

II. A.Materials

Ordinary Portland cement (P·O42.5) was used as the binding agent. Fine aggregate consisted of ordinary river sand, while coarse aggregate was a blend of crushed stones with particle sizes of 4.75–9.5 mm, 9.5–16 mm, and 16–26.5 mm, as specified in the Specifications for Construction of Aerodrome Cement Concrete Pavement (MH5006-2015) [20]. The proportions of each particle size were determined based on the minimum loose bulk density, with a ratio of 1:1:4. The physical properties of the aggregates are provided in Table 1, and the sand gradation curve, obtained from sieve analysis, is shown in Figure 1. A polycarboxylate superplasticizer (SP) was used as the water-reducing agent, meeting the performance requirements outlined in the Code for Concrete Admixture Application (GB 50119-2013) [21]. At room temperature, the superplasticizer is a colorless, transparent liquid, with its performance indicators listed in Table 2. Three different forms of rubber were used in the experiment: 3–5 mm rubber particles, 6–10 mm rubber particles, and 10–20 mm rubber fibers, as illustrated in Figure 2. Conventional tap water was used for mixing the concrete.

Table 1: The Physical properties of aggregates

Aggregate	Size (mm)	Specific Gravity	Unit weight (kg/m3)	Water absorption (%)	Fineness Modulus
Coarse aggregate	4.75-26.5	2.60	1623	1.2	-
Fine aggregate	-	2.68	1834	1.8	2.8
Rubber	3-20	1.25	-	-	-

Table 2: Technical indicators of polycarboxylate superplasticizer (SP)

Testing Item	Water Reduction Rate (%)	Air Content (%)	Setting Time Difference (min)	
			Initial Setting	Final Setting
Requirement	≥25	≤6.0	-90~+120	
SP	28	4.7	+25	+35

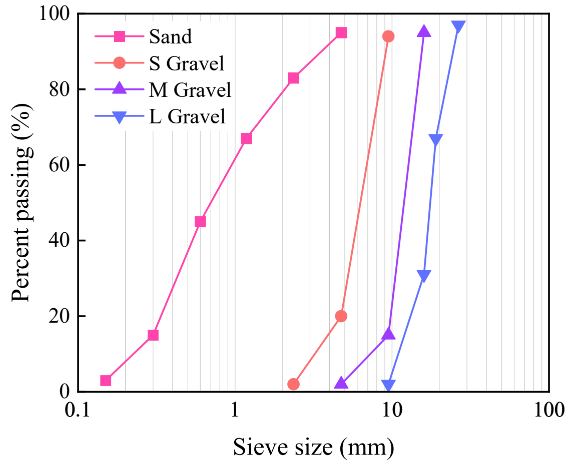


Figure 1: Gradation curve of the aggregate

Figure 2: Rubber used in the experiment

II. B.Mix design

A water-to-binder ratio of 0.4 was used. Rubber was incorporated into the concrete by replacing a portion of the sand by volume. Three types of rubber were selected: 3–5 mm rubber particles (Pra1), 6–10 mm rubber particles (Pra2), and 10–20 mm rubber fibers (Fib1). Rubberized concrete (RC) specimens were prepared with rubber replacement rates of 5%, 10%, 15%, and 20%. After uniform mixing of the materials, the fresh concrete was poured into molds and compacted on a vibrating table. The specimens were demolded after 24 hours and subsequently cured in a standard curing room for 28 days. The mix proportions are provided in Table 3.

Table 3: Concrete mixture proportion

Mix No.	Rubber Replacement Rate (%)	Mix proportions (Kg/m³)							
		Rubber	Sand	Cement	Water	S Gravel	M Gravel	L Gravel	SP
NC0	0%	0	630	350	140	223	223	890	2.5
RC5	5%	14.7	599	350	140	223	223	890	2.5
RC10	10%	29.4	567	350	140	223	223	890	2.5
RC15	15%	44.1	536	350	140	223	223	890	2.5
RC20	20%	58.8	504	350	140	223	223	890	2.5

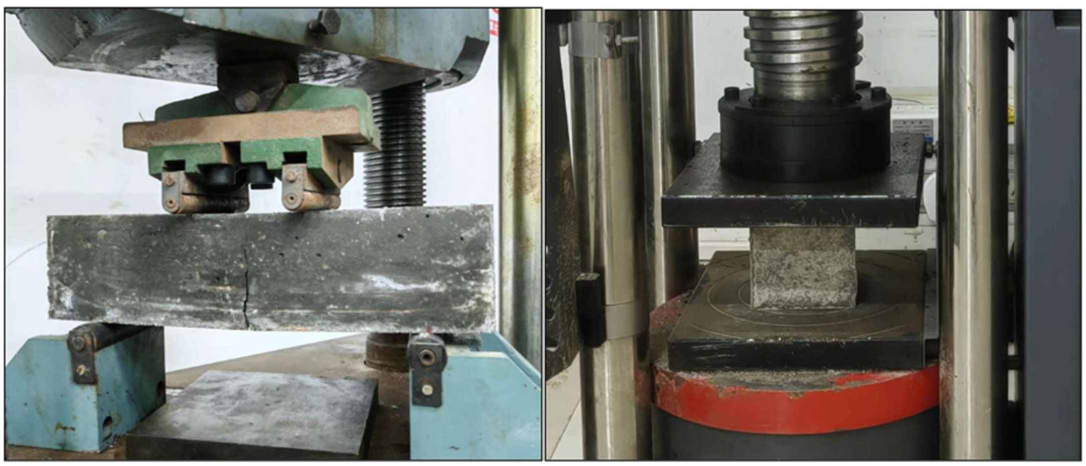
III. Experimental Program

III. A. Vebe consistency test

The consistency of the fresh concrete was tested to determine its workability. The concrete used in this experiment is classified as stiff concrete, characterized by a very dry and dense mix, resulting in a slump value approaching zero. Fluidity is typically measured using the Vebe consistency test, where a shorter Vebe time indicates better workability and fluidity of the concrete. The test was conducted according to the Testing Methods of Cement and Concrete for Highway Engineering (JTG 3420-2020) [22].

III. B. Compressive and Flexural test

In accordance with the Testing Methods of Cement and Concrete for Highway Engineering (JTG 3420-2020) [22], the compressive strength and flexural strength of rubberized concrete at 28 days were determined using a hydraulic universal testing machine, as shown in Figure 3. The compressive strength was tested using cubic specimens with dimensions of 100 mm × 100 mm × 100 mm, while the flexural strength was measured using prismatic specimens of 100 mm × 100 mm × 400 mm. The flexural test was performed using a four-point bending method for loading. Specimens were cured in a standard curing room at 20 ± 2°C and a relative humidity greater than 95% for 7 and 28 days. After reaching the specified test age, the specimens were removed from the curing environment, and the surface moisture was wiped off before conducting the compressive and flexural strength tests.



(a) Flexural test (b) Compressive test

Figure 3: Compressive and Flexural test

III. C. Flexural elastic modulus test

The flexural elastic modulus of rubberized concrete was determined using a hydraulic universal testing machine, following the Testing Methods of Cement and Concrete for Highway Engineering (JTG 3420-2020) [22]. The test setup included the use of displacement gauges to measure mid-span deflection, based on the flexural strength test apparatus. The specimens were prismatic, with dimensions of 100 mm × 100 mm × 400 mm, and five cycles of loading were applied. The load standard was set as half of the average ultimate flexural load, and the deflection was recorded from the fifth loading cycle. The flexural elastic modulus was calculated using the formula:

$$E_f = \frac{23L^3(F_{0.5} - F_0)}{1296J\left|\Delta_{0.5} - \Delta_0\right|} \tag{1}$$

where L is the span length between the supports of the specimen, $F_{0.5}$ is half of the ultimate flexural load, F_0 is the initial load, $\Delta_{0.5}$ and Δ_0 are the mid-span deflections corresponding to $F_{0.5}$ and F_0 respectively, and J is the moment of inertia of the cross-section.

IV. Experimental Results and Discussion

IV. A. Workability

The relationship between the Vebe time of fresh concrete and the rubber replacement rate is illustrated in Figure 4. The results show that the incorporation of rubber particles (Pra1, Pra2) enhanced the fluidity of the fresh concrete, which aligns with the findings of previous studies [23]. In contrast, the addition of rubber fibers (Fib1) reduced the fluidity of the mix. Specifically, as the rubber replacement rate increased, the Vebe time for rubber particle concrete exhibited a decreasing trend, while the Vebe time for concrete containing rubber fibers increased. At the same volume replacement rate, fresh concrete with 3–5 mm rubber particles showed a shorter Vebe time compared to that with 6–10 mm rubber particles, indicating that smaller rubber particles are more effective in improving the workability of fresh concrete.

These observed phenomena can be attributed to the hydrophobic nature of rubber, which has a lower water absorption rate compared to cement mortar. As a result, the addition of rubber increases the amount of free water in the mix, leading to a reduction in the Vebe time [23]-[25]. However, the inclusion of rubber fibers decreases fluidity because the fibers have poor flow characteristics and tend to clump together during mixing, which results in increased Vebe time.

It is noteworthy that previous studies involving the incorporation of rubber into ordinary plastic concrete found results contrary to those observed in stiff concrete. In those studies, the addition of rubber was found to reduce the slump of the concrete, thereby decreasing its fluidity. This is due to the rough surface of the rubber particles, which generates high friction between the particles and the aggregates [26], [27].

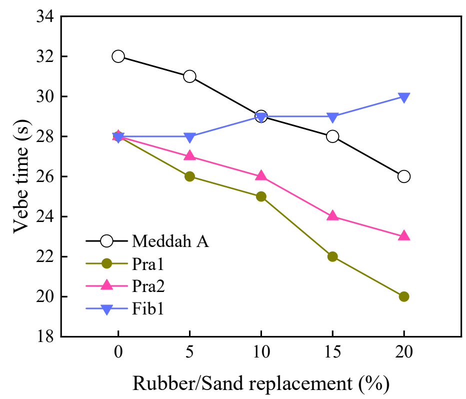


Figure 4: Effect of rubber content on workability

IV. B. Unit weight

The variation in the unit weight of rubber concrete as the rubber content increased is shown in Figure 5, with respect to the theoretical values (calculated based on the total amount of concrete materials). In this experiment, the mass of concrete specimens with three different types of rubber did not significantly differ under the same dosage conditions. Therefore, the test results for the concrete specimens containing 3–5 mm rubber particles were selected. As shown in Figure 5, the unit weight of rubberized concrete decreased as the rubber replacement rate increased, which is consistent with findings from previous research [25]. For example, when the rubber replacement rate increased from 0% to 20%, the unit weight decreased from 2440 kg/m³ to 2334 kg/m³, resulting in a loss of 4.3%. Similarly, Keleş Ö F et al. [28] observed a decrease of 5.3% in unit weight when 20% rubber powder was added to roller-compacted concrete mixtures. This reduction is primarily due to the lower density of rubber compared to traditional aggregates and the tendency of rubber particles to trap air during mixing, further reducing the unit weight of rubberized concrete [27], [29], [30].

IV. C. Compressive and flexural strength

The results for the compressive and flexural strength of the concrete are shown in Table 4 and Table 5. Figure 6 illustrates the variation in the flexural strength of rubberized concrete. As observed in the figure, the flexural strength of rubberized concrete decreases progressively with an increase in rubber content. Specifically, when the rubber replacement rate increases from 5% to 20%, the flexural strength of the three types of rubber concrete decreases from 2.4%, 3.1%, and 3.4% to 13.5%, 15.6%, and 20.5%, respectively. For the same rubber dosage, concrete with 3–5 mm rubber particles exhibits higher flexural strength compared to those containing 6–10 mm rubber particles and 10–20 mm rubber fibers. When the rubber replacement rate exceeds 10%, the flexural strength of concrete with 10–20 mm rubber fibers decreases rapidly, whereas the decline in flexural strength for the other two types of rubberized concrete is more gradual.

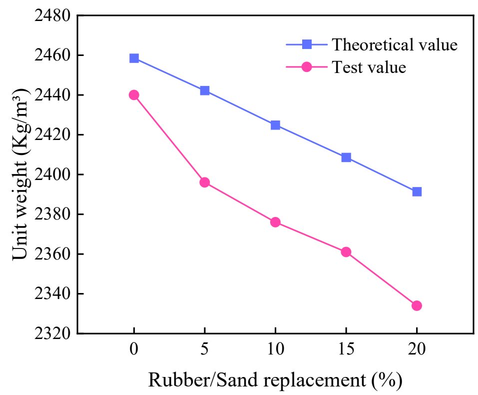


Figure 5: The unit weight of rubber concrete

The incorporation of rubber reduces the strength of concrete, primarily due to the poor bonding capacity between the rubber particles and the cementitious matrix. Rubber particles act as weak points within the concrete; the higher the rubber content, the greater the number of weak points introduced, resulting in a greater decline in flexural strength [28]. When the rubber replacement rate exceeds 10%, the strength of rubberized concrete with rubber fibers decreases rapidly because the fibers tend to clump together, leading to increased stress concentration as the dosage increases. Rubberized concrete with 3–5 mm rubber particles shows a slower decline in strength compared to that with 6–10 mm rubber particles. This is because smaller rubber particles have a larger surface area, which consumes more cementitious material, leading to a stronger bond between the rubber particles and the concrete matrix. Therefore, rubberized concrete with smaller rubber particles has higher strength than that with larger particles [24].

Table 4: Flexural strength

Mix No.	28d Flexural strength (MPa)		
	3-5mm rubber particles	6-10mm rubber particles	10-20mm rubber fibers
NC0	5.85	5.85	5.85
RC5	5.71	5.67	5.65
RC10	5.52	5.44	5.42
RC15	5.25	5.15	5.07
RC20	5.06	4.94	4.65

Table 5: Compressive strength

Mix No.	3-5mm rubber particles		6-10mm rubber particles	
	7d Compressive strength	28d Compressive strength	7d Compressive strength	28d Compressive strength
NC0	34.67	43.23	34.67	43.23
RC5	30.52	40.22	30.86	39.82
RC10	27.64	36.71	27.97	36.43
RC15	25.14	33.94	25.28	33.32
RC20	23.44	31.85	23.47	31.47

Figure 7 shows the failure patterns of the specimens. It can be observed that the failure crack in the reference concrete forms a straight line along the center, whereas the failure cracks in the rubber-incorporated concrete are more irregular. From the failure patterns, it is evident that each specimen has a single continuous crack, indicating that the incorporation of rubber did not significantly improve the brittleness of the concrete. This aligns with the findings of Kardos and Durham et al. [31], who noted that using waste rubber in roller-compacted concrete pavements does not effectively prevent cracking but rather helps to impede the propagation of cracks.

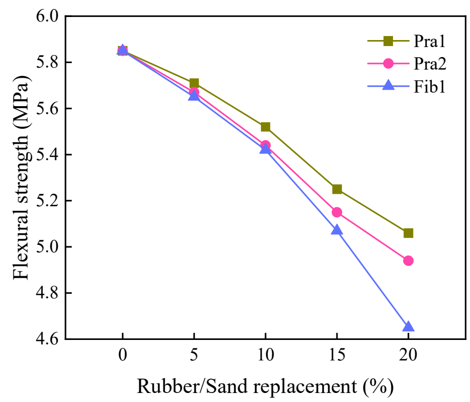


Figure 6: Flexural strength of rubber concrete

(a) Normal concrete

(b) Rubber particles concrete

(c) Rubber fiber concrete

Figure 7: Failure modes of concrete flexural test specimens

Figure 8 shows the variation in the ratio of compressive strength of rubber concrete at 7 days to that at 28 days. It can be observed that as the rubber content increases, the strength ratio between 7 days and 28 days gradually decreases, which is consistent with the trend identified by previous researchers [32]. Additionally, the decline is more pronounced in rubberized concrete with smaller particles. When the rubber content changes from 0% to 5%, the rate of decline in the strength ratio is relatively rapid; however, when the content exceeds 5%, the rate of decline becomes more gradual. The experimental results indicate that the incorporation of rubber suppresses the early strength development of concrete, with smaller rubber particles having a stronger suppressive effect. High early strength in concrete often accompanies elevated hydration heat and shrinkage, which can lead to microcracking and affect the durability of the concrete. Incorporating rubber into concrete can help prevent the formation of microcracks.

Figure 9 illustrates the relationship between the strength loss rate (Δf/f) and the rubber content. It can be seen that as the rubber content increases, the strength loss rate of the concrete gradually increases, with compressive strength experiencing a faster loss compared to flexural strength. This suggests that compressive strength is more sensitive to changes in rubber content than flexural strength. Similar conclusions have also been drawn by Meddah A et al. [23]. Compared to plastic concrete used in building structures, dry hard concrete is less sensitive to the incorporation of rubber, resulting in a smaller decline in strength as the rubber content increases [24], [32], [33]. This is because dry hard concrete has low fluidity and a low water-to-cement ratio, which helps mitigate negative effects such as rubber flotation. In this experiment, various single-sized aggregates were used in the concrete mix, and the incorporation of rubber particles helped fill the gaps between the aggregates, making the concrete denser and reducing the strength decline.

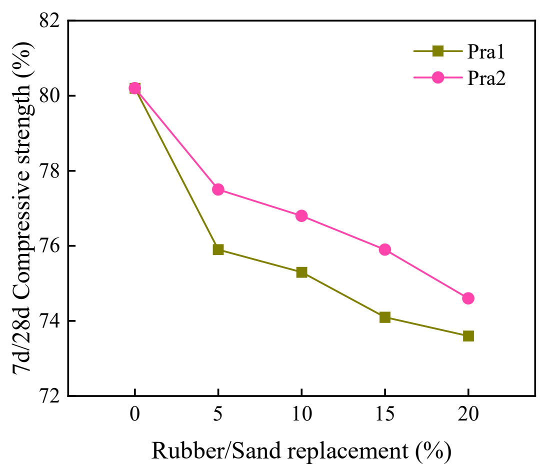


Figure 8: Variation in the compressive strength ratio

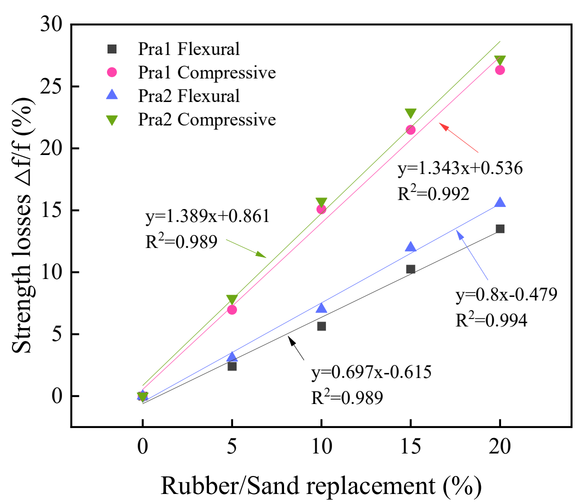


Figure 9: The strength loss rate of rubber concrete

IV. D. Flexural elastic modulus

Figure 10 shows the variation in the flexural elastic modulus of rubberized concrete. The test results indicate that the flexural elastic modulus of rubberized concrete decreases progressively as the rubber replacement ratio increases. Specifically, when the rubber replacement ratio increases from 5% to 20%, the flexural elastic modulus of the three types of rubberized concrete decreases from 5.8%, 4.3%, and 7.1% to 20.3%, 18.5%, and 20.9%, respectively. Under the same replacement ratio, rubberized concrete with 10–20 mm rubber fibers exhibits the lowest flexural elastic modulus, while rubberized concrete with 3–5 mm rubber particles shows a lower modulus compared to that with 6–10 mm rubber particles.

The incorporation of rubber reduces the flexural elastic modulus of concrete because rubber has a very low modulus of elasticity and can undergo significant deformation [33]. Smaller rubber particles are more evenly distributed within the concrete, resulting in a lower flexural modulus compared to concrete with larger rubber particles. Compared to rubber particles, rubber fibers have a more pronounced effect in reducing the flexural elastic modulus of rubberized concrete. This is primarily because rubber fibers embed themselves in the concrete, and their overlapping forms a network structure that allows the rubberized concrete to accommodate larger deformations.

Figure 11 shows the relationship between the flexural elastic modulus of rubberized concrete and its flexural strength. From the figure, it can be observed that the flexural modulus of rubberized concrete decreases as the flexural strength decreases, indicating a strong correlation between the flexural strength and the flexural modulus of rubberized concrete.

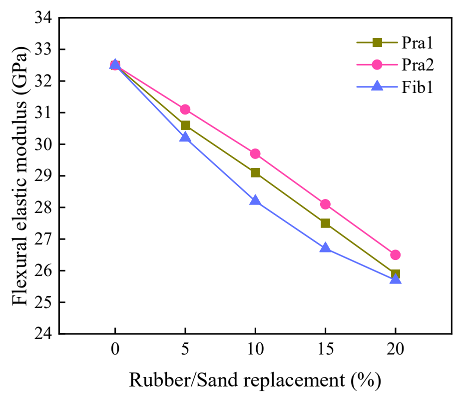


Figure 10: The flexural elastic modulus of rubberized concrete

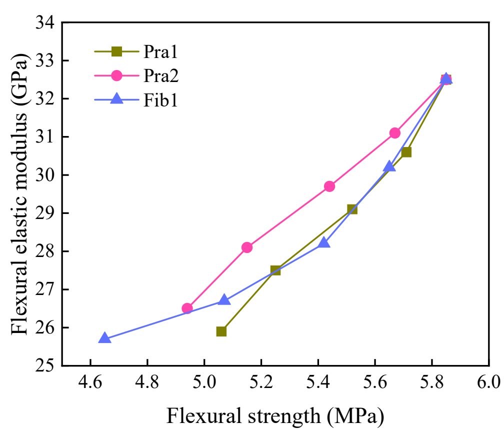


Figure 11: The relationship between the flexural strength and elastic modulus

V. Conclusions

This study conducted experimental research on the workability and mechanical properties of rubberized concrete, with a particular focus on its application in airport pavement engineering. The effects of various rubber forms and replacement rates on key performance indicators, such as concrete consistency, compressive strength, flexural strength, and flexural elastic modulus, were evaluated through experimental testing. Based on the results, the following conclusions can be drawn:

(1) As the rubber replacement ratio in concrete increases, the workability of concrete with rubber particles gradually improves, whereas the workability of concrete incorporating rubber fibers decreases. Additionally, the unit weight of the concrete decreases with an increase in the rubber replacement ratio, due to the relatively low density of rubber, which reduces the overall density of the concrete.

(2) With varying rubber incorporation, both the compressive and flexural strengths of rubberized concrete decrease progressively as the rubber replacement ratio increases. Notably, compressive strength declines more rapidly than flexural strength. The addition of rubber also delays the early strength development of concrete. At the same rubber replacement ratio, concrete with 3–5 mm rubber particles demonstrates relatively higher compressive and flexural strengths compared to mixes with larger rubber particles or rubber fibers.

(3) As the rubber replacement ratio increases, the flexural elastic modulus of rubberized concrete decreases across all three rubber forms. Among the mixes, concrete containing 10–20 mm rubber fibers shows the lowest flexural elastic modulus at the same replacement ratio. The results indicate that incorporating rubber into concrete effectively reduces its flexural elastic modulus.

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