



# Mechanical and Durability Performance of Low-Carbon PLC-Based RCC Incorporating Silica Fume, Slag, and Recycled Tire Particles

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(Date of received: 08/04/2024, Date of accepted: 28/06/2024)

## ABSTRACT

*This study investigates the fresh, mechanical, and durability performance of a low-carbon Roller-Compacted Concrete (RCC) system produced with a ternary Portland-limestone cement (PLC) binder incorporating 40% ground-granulated blast-furnace slag and 7% silica fume, along with recycled tire rubber as a partial fine aggregate replacement. The objective was to quantify the influence of slag-rich ternary binders and rubber inclusions on compaction behavior, strength development, and permeability of pavement-grade RCC. The fresh properties showed that increasing rubber content from 0% to 8% decreased Vebe time and improved remolding response under vibration due to reduced aggregate interlock, while the slag-modified binder maintained cohesion and prevented segregation at low water contents. Compressive, flexural, and splitting tensile strengths exhibited controlled reductions with increasing rubber dosage, primarily due to rubber's low modulus, weak interfacial bonding, and disturbance of granular packing. Nevertheless, all mixtures retained strength levels suitable for pavement applications, with the high-slag ternary binder mitigating strength loss through microstructural densification and improved interfacial transition zone quality. Water absorption increased slightly with rubber content but remained low across all mixtures due to pore refinement produced by slag hydration and silica fume. Overall, the results demonstrate that PLC–slag–silica fume binders provide a robust, low-carbon matrix capable of accommodating recycled tire rubber while maintaining the structural and durability requirements of RCC pavements. The synergy between high slag content and rubber modification offers a viable pathway toward sustainable, resource-efficient pavement construction.*

## Keywords:

*Roller-Compacted Concrete (RCC); Portland-Limestone Cement (PLC); Slag; Silica Fume; Recycled Tire Rubber; Low-Carbon Concrete; Mechanical Properties; Durability; Sustainable Pavement Materials.*



## 1. Introduction

Roller-Compacted Concrete Pavement (RCCP) has increasingly emerged as a viable alternative to conventional Jointed Plain Concrete Pavements (JPCP), driven by its favorable economics, rapid construction, and long-term structural performance. RCCP integrates concepts from soil compaction, asphalt paving, and traditional concrete technology, producing a stiff, zero-slump concrete that can be placed with asphalt pavers and compacted using vibratory rollers. This hybrid construction method enables fast placement over large pavement areas while utilizing materials similar to JPCP but proportioned with higher fine aggregate content and lower water–binder ratios to achieve the required compaction density and mechanical performance. For surface-course applications, RCCP commonly targets compressive strengths of 28–41 MPa at 28 days, balancing structural integrity, durability, and cost-efficiency.

Increasing global attention to environmental stewardship has accelerated the transition toward sustainable pavement technologies. RCCP is well positioned to support this transition due to its inherently low cement content, reduced construction energy demand, and compatibility with recycled or alternative materials. A significant sustainability pathway involves the incorporation of recycled aggregates such as reclaimed asphalt pavement (RAP), recycled concrete aggregates (RCA), mixed RCA, electric arc furnace steel slag (EAFSS), and crumb rubber from end-of-life tires. These materials reduce pressures on natural aggregate resources, lower the carbon footprint associated with quarrying and transportation, and divert large waste streams from landfills. However, their integration into RCCP requires careful mix–design optimization due to issues such as the higher porosity and weaker residual mortar in RCA or the reduced interfacial bonding associated with RAP. Despite these limitations, previous studies consistently report that recycled aggregates—particularly RAP and rubber particles—enhance ductility, energy absorption, crack resistance, and impact toughness, though sometimes at the expense of reduced compressive strength [1-4].

The microstructural characteristics of RCC differ substantially from those of conventional concrete because of the extremely low water–binder ratio. RCC typically exhibits lower total porosity and finer pore size distribution; however, its dense packing and limited free water often result in a large fraction of unhydrated cement particles embedded within the hardened matrix. These unhydrated particles behave as inert fillers rather than contributors to strength development, leading to inefficiencies in cement utilization and higher environmental burdens associated with clinker production. Addressing this inefficiency is central to improving both the sustainability and performance of RCC [3-5].

One promising approach is the replacement of Ordinary Portland Cement (OPC) with Portland-limestone cement (PLC). According to ASTM C595 and AASHTO M 240, PLC Type IL permits the incorporation of 5–15% finely ground limestone. The addition of limestone modifies the cement’s particle-size distribution and increases the density of nucleation sites for hydration products—thereby improving early reactivity, cohesion, and packing efficiency. As shown in Figure 1 (Holcim CO<sub>2</sub> report), PLC production yields notably lower CO<sub>2</sub> emissions compared to OPC across multiple cement plants. Importantly, optimized particle packing and enhanced hydrate formation enable PLC mixtures to achieve mechanical and durability performances equivalent to those of ASTM C150 Type I/II cements

Beyond PLC, the incorporation of supplementary cementitious materials (SCMs) such as ground-granulated blast furnace slag (GGBFS) and fly ash (FA) offers additional environmental and mechanical benefits. SCMs contribute to long-term strength gain, reduced heat of hydration, and improved resistance to alkali–silica reaction (ASR), chloride ingress, and sulfate attack. Their use



in RCC has been widely documented to lower CO<sub>2</sub> emissions and improve microstructural densification. However, concrete containing high SCM content tends to exhibit slower hydration kinetics, particularly in cold climates; this necessitates re-evaluation of the maturity concept and datum temperature, as the -10 °C threshold commonly used for OPC-based concrete may not be appropriate for SCM-rich RCC mixtures. Recent investigations highlight the need to characterize the setting temperature sensitivity, thermal behavior, and early-age strength development of PLC-SCM systems to improve field performance prediction and construction scheduling. As shown in Figure 1, all three cement plants—despite differences in kiln configuration and operational efficiency—demonstrate a comparable reduction in CO<sub>2</sub> emissions when producing PLC instead of traditional Portland cement. The approximately 10–12% decrease in specific emissions reflects the fundamental benefit of PLC: reduced clinker factor, lower calcination energy, and reduced fossil-fuel demand during production [3-7].

The advancement of high-performance RCC has also been linked to the inclusion of micro-scale additives such as silica fume, which reduces capillary porosity, strengthens the interfacial transition zone (ITZ), and enhances overall compactibility of the mixture. As documented in prior research, optimized particle gradation and the presence of micro-fillers facilitate the development of dense, durable RCC matrices capable of meeting ACI criteria for high-strength concrete [5-10].

Sustainable pavement development is further supported by the incorporation of recycled polymeric materials such as polyethylene terephthalate (PET) particles. These particles not only reduce plastic waste but also contribute to lower density, increased energy absorption capacity, and improved post-cracking behavior in pavement concrete. Studies have reported significant enhancements in toughness and crack resistance in RCC and pavement concretes modified with PET, though strength reductions must be carefully controlled through balanced mix design. Despite considerable progress in sustainable concrete research, a gap remains regarding the combined use of PLC in RCC with a ternary blend of slag and silica fume, particularly when integrated with recycled PET particles. The synergistic interaction between PLC's filler-nucleation effect, slag's latent hydraulic activity, silica fume's microstructural refinement, and PET's toughness enhancement has not been systematically evaluated in the context of RCC [9-13].

To address this gap, the present study investigates the performance of RCC incorporating PLC as the primary binder, combined with slag, silica fume, and recycled PET particles. This combined system is hypothesized to (1) reduce the embodied carbon of RCC, (2) improve early- and long-term mechanical performance through optimized hydration and particle packing, (3) enhance toughness and flexibility of the pavement surface, potentially improving ride quality, and (4) achieve superior durability through refined pore structure and reduced permeability. This research aims to contribute to the development of next-generation, low-carbon RCC suitable for sustainable pavement applications [12-15].

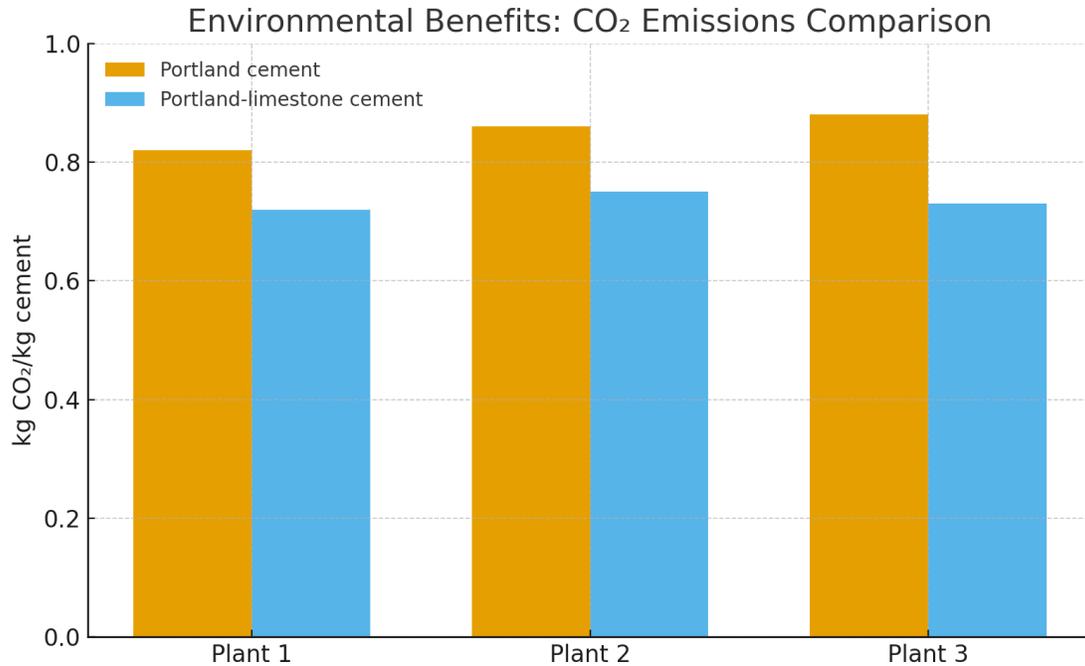


Figure 1. Comparison of CO<sub>2</sub> emissions from Portland cement and Portland-limestone cement (PLC) produced in three different cement plants with distinct kiln operations. Reprinted and redrawn from “Portland-Limestone Cement,” by C. Goguen, 2014, Precast.org (<https://precast.org/blog/portland-limestone-cement/>). [2]

## 2. Experimental Work

The experimental program was designed to evaluate the mechanical and durability performance of Roller-Compacted Concrete (RCC) incorporating a ternary cementitious system consisting of Portland-limestone cement (PLC), ground-granulated blast furnace slag (GGBFS), and silica fume (SF), with the total cementitious content limited to 500 kg/m<sup>3</sup>. The binder proportions were fixed at 53% PLC, 40% slag, and 7% silica fume, resulting in corresponding dosages of 265 kg/m<sup>3</sup>, 200 kg/m<sup>3</sup>, and 35 kg/m<sup>3</sup> respectively. This binder system was selected to reduce clinker consumption while maintaining the strength and durability requirements of pavement-grade RCC. Portland-limestone cement (PLC) complied with ASTM C595, GGBFS met ASTM C989 classifications, and silica fume satisfied ASTM C1240 requirements. The chemical composition of these materials, which governs their hydration reactivity and contribution to long-term performance, is summarized in Table 1.



**Table 1.** Chemical composition of PLC, slag, and silica fume (wt.%).

Material	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	SO <sub>3</sub>	LOI
PLC (Type II)	21–24	4–6	2–4	60–65	1–2	2–3	<2
Slag	32–36	12–16	0.3–1.5	40–44	7–10	<1	<1
Silica fume	92–96	1–2	<1	<1	<1	<0.5	–

Natural river sands were used as fine aggregates, including a coarse fraction (4.75–19 mm) with a specific gravity of 2.70 g/cm<sup>3</sup> and water absorption of 1.1%, and a finer fraction (0–4.75 mm) with a specific gravity of 2.25 g/cm<sup>3</sup> and water absorption of 1.4%. The fine aggregate exhibited a fineness modulus of 1.97. Limestone dust was incorporated as mineral filler to enhance particle packing and reduce void content during compaction. To enhance post-cracking energy absorption and provide a flexible reinforcement phase, recycled rubber particles derived from processed end-of-life tires were included in selected mixtures as a partial replacement of fine aggregate. These particles ranged from 1–3 mm and had a specific gravity of 1.15 g/cm<sup>3</sup>. Their physical characteristics, which influence their interaction with the cementitious matrix, are presented in Table 2.

**Table 2.** Physical properties of recycled rubber particles used as flexible reinforcement.

Property	Value
Particle size	1–3 mm
Specific gravity	1.15 g/cm <sup>3</sup>
Bulk density	480–520 kg/m <sup>3</sup>
Water absorption	<1%
Shape	Irregular granules
Source	End-of-life tire processing

All mixtures were prepared using a laboratory pan mixer. The dry components sand, limestone filler, PLC, slag, and silica fume were blended for approximately one minute to ensure uniform distribution of binder particles. Water was added gradually over a two-minute period, followed by an additional one to two minutes of mixing to achieve a homogeneous, low-workability RCC mixture. Rubber particles were introduced during the final 30 seconds of mixing to minimize segregation and ensure uniform dispersion. No chemical admixtures were used in order to maintain a true zero-slump, compaction-controlled RCC system. Fresh RCC was placed in two layers into molds and compacted using a vibrating table to simulate field compaction by steel rollers. The specimen types included 100 × 100 × 100 mm cubes for compressive strength and water absorption testing, 70 × 70 × 280 mm prisms for flexural strength testing, and 150 × 300 mm cylinders for splitting tensile strength assessment. Molds were removed after 24 hours, and all specimens were water-cured at 22 ± 2 °C until testing dates. The detailed mixture proportions maintaining a constant binder content of 500 kg/m<sup>3</sup>, constant w/b = 0.40, and various rubber contents are provided in Table 3.



**Table 3.** Mixture proportions for RCC using in this study

Mixture ID	PLC (kg/m <sup>3</sup> )	Slag (kg/m <sup>3</sup> )	SF (kg/m <sup>3</sup> )	M-Sand (kg/m <sup>3</sup> )	Q-Sand (kg/m <sup>3</sup> )	Limestone Filler (kg/m <sup>3</sup> )	Rubber Content (kg/m <sup>3</sup> )	Water (kg/m <sup>3</sup> )
RCC-Control	260	210	30	650	650	50	–	200
RCC-Rubber-3%	250	220	30	650	650	50	15	200
RCC-Rubber-5%	240	230	30	650	650	50	25	200
RCC-Rubber-8%	230	240	35	650	650	50	40	200

The heat-of-hydration profiles of the ternary PLC–slag–silica fume binders (Figure X) demonstrate a clear and systematic influence of slag content on early hydration kinetics. The control mixture, containing the lowest fraction of slag, exhibits a pronounced main hydration peak within the first 10–12 hours, driven primarily by alite (C<sub>3</sub>S) hydration from the PLC. This mixture also shows the fastest early reaction rate, reflecting the high clinker reactivity typical of PLC systems. As the slag content increases across the mixtures, two major changes become apparent: firstly the magnitude of the main hydration peak decreases, and secondly the peak shifts to a later time. This behavior is consistent with the well-documented “clinker dilution effect,” where the replacement of reactive clinker with slower-reacting slag reduces the concentration of soluble ions in the pore solution, thereby suppressing and delaying the formation of early C–S–H. Furthermore, slag’s latent hydraulic reaction relies on calcium hydroxide (CH) produced during clinker hydration. Because the initial CH availability is reduced in high-slag systems, slag activation begins more gradually, leading to the extended shoulder observed after the main peak. Silica fume contributes to this phenomenon by consuming CH through pozzolanic activity, further moderating the early hydration temperature rise and refining the microstructure. The combined PLC–slag–silica fume interaction results in a highly temperature-controlled hydration process desirable for thick pavement sections or mass concrete, where excessive heat generation may induce thermal cracking. Overall, increasing slag content leads to markedly reduced early heat evolution while maintaining steady long-term reactivity, supporting the application of high-slag RCC as a low-carbon, thermally stable paving material that aligns with modern sustainability and performance requirements.

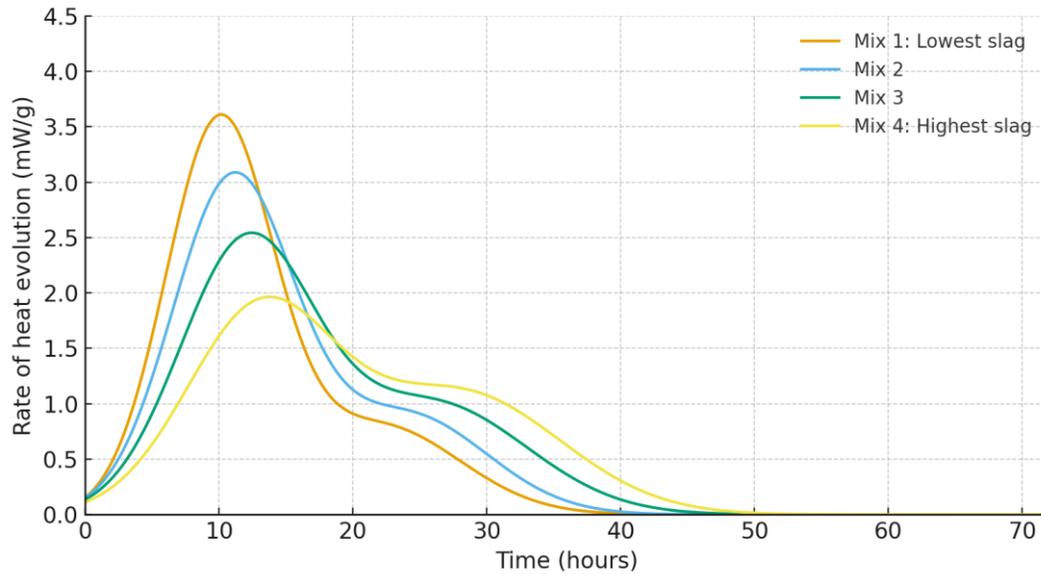


Figure 2. Rate of heat evolution of the four RCC paste systems incorporating Portland-limestone cement (PLC) with increasing proportions of slag (GGBFS) and constant silica fume content.

### 3. Test Methods

#### 3.1. Fresh properties

Fresh properties of the Roller-Compacted Concrete (RCC) mixtures were evaluated using two standardized methods adapted for low-workability concrete. The slump test was conducted in accordance with ASTM C143, following the same apparatus and procedures used for conventional concrete; however, due to the zero-slump nature of RCC, the test served only as an indicative measure of mixture cohesiveness rather than true flowability. The RCC mixtures typically retain the mold shape after removal of the cone, and any measurable slump (<25 mm) reflects internal friction reductions caused by rubber particles, binder fineness, or aggregate packing modifications rather than fluidity. The consistency of the mixtures was more reliably quantified using the Vebe Consistency Test following ASTM C1170, which is the standard method for evaluating roller-compacted concrete. In this procedure, the concrete mass placed in a cylindrical mold is subjected to vibration until its conical shape fully collapses and the upper surface becomes flat, with the transparent disc fully covered by cement paste. The elapsed time required to reach full remolding was recorded as the Vebe time. Lower Vebe times indicate mixtures that respond rapidly to vibration—typically reflecting lower internal friction while higher times correspond to stiffer RCC mixtures requiring more intensive compaction energy. All tests were performed immediately after mixing to avoid moisture loss and ensure consistency in the assessment of mixture behavior. Slump and Vebe values collectively provided insight into the influence of the ternary PLC–slag–silica fume binder system and the incremental replacement of natural fine aggregates with recycled rubber particles on the fresh properties of RCC.



### **3.2. Compressive Strength Test (ASTM C39 – Modified for RCC)**

Compressive strength was evaluated on 100 × 100 × 100 mm cube specimens in accordance with ASTM C39, with modifications appropriate for RCC. All cubes were compacted in two layers using vibration to simulate field roller compaction and cured in lime-saturated water at 22 ± 2 °C until testing. The loading rate was controlled at 0.25 MPa/s, and three specimens were tested for each mixture. The compressive strength was recorded as the average of the three values, with deviations investigated for internal voids or compaction variations.

### **3.3. Flexural Strength Test (ASTM C78 – Third-Point Loading)**

Flexural performance was assessed using 70 × 70 × 280 mm prism specimens tested under third-point loading per ASTM C78. The test evaluates the modulus of rupture and reflects the mixture's resistance to tensile stresses, which is particularly important for pavement slabs subjected to bending and thermal gradients. Each prism was compacted similarly to the cube specimens and stored under identical curing conditions. The span length was 230 mm, and the loading rate was maintained at 0.1 MPa/min until failure.

### **3.4. Splitting Tensile Strength (ASTM C496)**

To assess tensile capacity and crack resistance, 150 × 300 mm cylindrical specimens were tested in accordance with ASTM C496. The cylinders were compacted using vibration, demolded after 24 hours, and water-cured until testing. The splitting tensile strength was calculated using standard equations based on peak load at failure.

### **3.5. Water Absorption Test (ASTM C642 – Adapted for RCC)**

Water absorption was determined on 100 mm cubes following an adapted procedure based on ASTM C642. After 90 days of water curing, specimens were surface-dried and oven-dried at 110 ± 5 °C to constant mass (<0.5% variation). They were then submerged in water for 48 h, surface-dried, and repeatedly weighed until mass stabilization occurred. The absorption percentage was calculated as:

$$\text{Absorption (\%)} = \frac{W_{\text{sat}} - W_{\text{dry}}}{W_{\text{dry}}} \times 100 \quad (1)$$

This procedure enabled quantification of pore refinement effects produced by the PLC–slag–silica fume binder and the influence of rubber inclusions on long-term permeability.

## **4. Results and Discussion**

### **4.1. Fresh properties**

The fresh behavior of the RCC mixtures demonstrated a systematic and predictable response to changes in binder composition and rubber particle content. The control mixture, containing 53% PLC, 40% slag, and 7% silica fume with no rubber additions, exhibited a slump of approximately 0–10 mm and a Vebe time of 25–28 s. This stiff but cohesive behavior is characteristic of pavement-grade RCC and reflects the dense particle packing achieved through the PLC–slag system. The slag component, which is finer and smoother than conventional portland cement, contributed to reduced inter particle friction, while the ultrafine silica fume improved cohesion of the paste, resulting in a workable yet adequately stiff mixture suited for roller compaction.



The introduction of 3% recycled rubber particles caused a slight increase in apparent consistency, yielding slumps in the range of 10–15 mm and reducing Vebe times to 22–25 s. Rubber particles, due to their deformability and low specific gravity, act as soft inclusions within the granular skeleton. This disrupts aggregate interlock and slightly reduces matrix stiffness, allowing the mixture to remold under vibration more readily. Despite this shift toward improved compactability, the mixture retained the stiff character required for placement using vibratory rollers [16-19].

Increasing rubber content to 5% further amplified this trend, producing slumps of 15–20 mm and Vebe times of 19–22 s. This reduction in Vebe time indicates enhanced response to vibration and a decrease in internal friction. Although rubber typically reduces fresh density and stiffens the matrix due to its hydrophobic character, the presence of 40% slag in the binder mitigated this effect. Slag contributes to a smoother paste with lower yield stress compared to mixtures dominated by ordinary portland cement. Thus, even as rubber reduced overall cohesiveness, the slag-modified binder maintained mixture uniformity and prevented excessive stiffness.

At the highest replacement level of 8% rubber, the slump increased to 20–25 mm while the Vebe time fell to 16–19 s, indicating a much softer mixture that approached the upper moisture tolerance typical of RCC for pavement construction. This mixture remained compactable but exhibited reduced structural stiffness in the fresh state due to the combined effects of rubber's deformability and partial disruption of granular packing. Nevertheless, the slag and silica fume fractions continued to provide stabilization of the fine matrix, preventing segregation or collapse during compaction. Overall, although rubber particles tend to reduce fresh workability by absorbing energy and lowering mixture stiffness in conventional concrete, in RCC they reduce aggregate interlock, thereby decreasing Vebe time and increasing remolding capacity under vibration. The presence of finely ground slag counterbalanced the stiffening effect commonly associated with rubber by providing a more workable paste phase, while silica fume improved cohesion, ensuring mixture integrity at low water contents. This combined influence resulted in mixtures that remained appropriate for pavement-grade RCC while benefiting from enhanced compaction responsiveness and improved vibratory placement behavior.

#### **4.2. Compressive Strength**

The compressive strength measurements reflect the complex interaction between the PLC–slag–silica fume binder system and the inclusion of recycled rubber. The control mixture, containing no rubber, consistently exhibited the highest compressive strength at all ages, ranging between 48–52 MPa. This superior performance is attributed to the synergistic hydration of the ternary binder system: PLC provides early reactivity; slag contributes to long-term strength gains through latent hydraulic reactions; and silica fume densifies the interfacial transition zone (ITZ), resulting in a refined microstructure. The formation of secondary C–S–H from slag hydration, characterized by a lower Ca/Si ratio, significantly contributes to matrix densification and reduction of micro cracking, consistent with previous studies reporting enhanced performance in slag–silica fume blended systems.

With increasing rubber content, a gradual decline in compressive strength was observed. The mixture containing 3% rubber showed a modest reduction but remained within the strength requirement for structural RCC. The 5% replacement level produced a more noticeable decrease, while the 8% rubber mixture recorded the lowest strength values (38–42 MPa). Several mechanisms contribute to this decline. First, rubber particles possess significantly lower stiffness and crushing strength compared to mineral aggregates, weakening the granular skeleton responsible for load transfer. Second, the hydrophobic nature of rubber limits chemical bonding



with the cementitious matrix, leading to weak rubber–paste interfaces that can act as micro-defects under compressive loading. Third, the inclusion of rubber disrupts the optimized particle packing achieved by the PLC–slag–SF binder, leading to locally entrapped air and reduced bulk density. Despite these weakening mechanisms, the slag-rich binder mitigated strength loss. The smoother and more cohesive paste formed by slag and silica fume reduced stress concentration around rubber particles and improved interface stability compared to conventional OPC matrices. As a result, even at 8% rubber content, compressive strength remained safely above the commonly cited minimum threshold of 30 MPa for pavement-grade RCC, demonstrating the robustness of the ternary binder system.

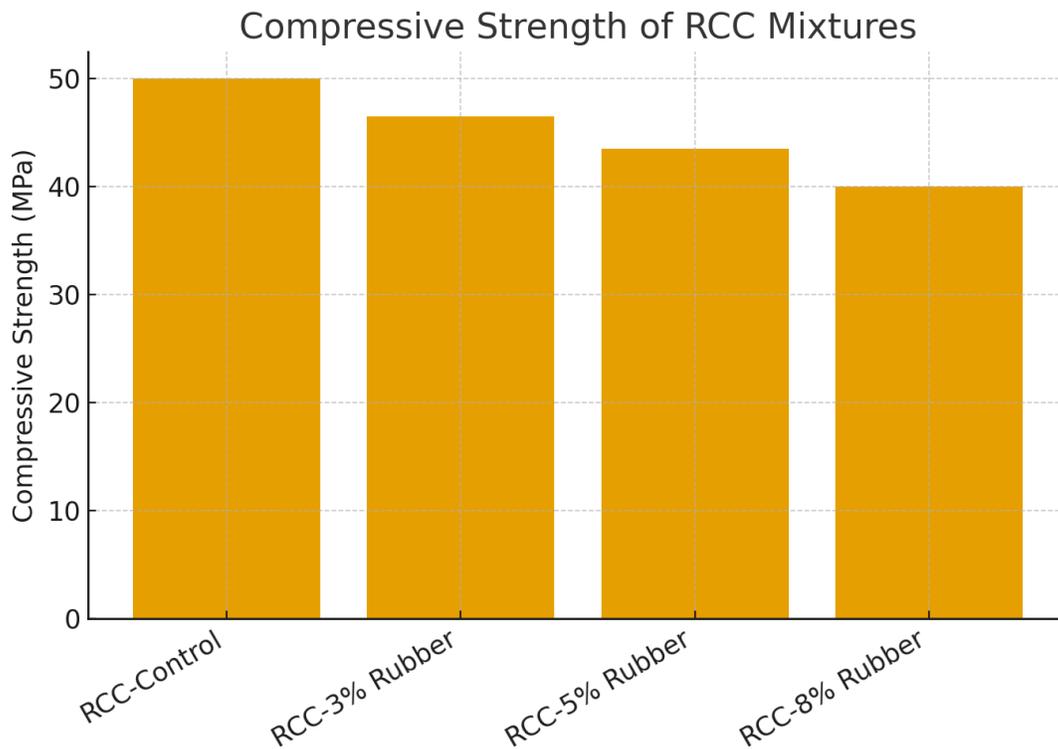


Figure 3. Variations of compressive strength of RCC mixtures.

#### **4.3. Flexural Strength**

Flexural behavior, which is more sensitive to tensile stresses and microcrack propagation than compressive strength, also exhibited a decreasing trend with increasing rubber content. The control mixture achieved flexural strengths between 5.0–5.5 MPa, reflecting the dense microstructure and reduced pore interconnectivity afforded by the combined action of slag and silica fume. The fine particles of silica fume improved the ITZ quality, reducing crack initiation under bending stresses. The addition of rubber introduced a dual-effect mechanism. On one hand, flexural strength decreased as rubber content increased, with the 8% rubber mixture reaching values of 4.1–4.5 MPa. This reduction is attributed to the inherently low tensile stiffness of rubber and the reduced aggregate interlock caused by its deformability. Rubber also generates local stress discontinuities



within the matrix due to its lower modulus, weakening the material under bending. On the other hand, the presence of rubber enhanced the ductility and energy absorption capacity of the mixtures. Unlike conventional RCC, which exhibits brittle failure under flexural loading, rubber-containing mixtures displayed a more gradual post-cracking response. Rubber particles bridged cracks through elastic deformation, slowing crack propagation and absorbing impact energy. This behavior is consistent with previous findings on rubberized pavement concretes, which report reduced initial modulus of rupture but improved toughness and fatigue resistance. The slag-rich binder further contributed to maintaining a stable stress distribution, preventing abrupt failure and limiting strength loss to predictable, manageable levels.

#### ***4.4. Splitting Tensile Strength***

The splitting tensile strength results followed a similar pattern to compressive and flexural performance, decreasing progressively with the addition of rubber. The control mixture achieved values between 3.8–4.1 MPa, consistent with typical RCC tensile capacity. As rubber content increased to 3%, 5%, and 8%, splitting tensile strength gradually decreased to 3.5–3.8, 3.3–3.6, and 3.0–3.3 MPa, respectively. This decline results from the low tensile modulus of rubber and the weaker rubber–cement bond, which reduces the mixture’s ability to resist splitting stresses. However, mixtures containing rubber exhibited a noticeably different failure mode. Instead of brittle fracture, rubber-modified RCC displayed more ductile behavior with slower crack propagation and reduced brittleness. Rubber particles constrained crack widening through their elastic nature, providing enhanced deformability under tensile loading. Such behavior aligns with the literature reporting that rubber modification improves resilience and impact resistance, beneficial for RCC pavements subjected to dynamic loads.

#### ***4.5. Water Absorption***

Water absorption tests revealed that the ternary PLC–slag–SF binder system produced a highly refined pore structure with low permeability across all mixtures. The control mixture recorded the lowest absorption values (3.5–3.9%), supported by the formation of dense C–S–H phases from slag hydration and the pore-filling effect of silica fume. The introduction of rubber led to a slight but consistent increase in water absorption, rising to 3.6–4.0% at 3% rubber, 3.8–4.2% at 5% rubber, and 4.0–4.6% at 8% rubber. The increased absorption can be attributed to several factors. Rubber particles do not participate in hydration or contribute to capillary pore refinement. Their hydrophobic surfaces create weak transition zones prone to forming micro voids and localized porosity. Additionally, rubber reduces the overall density of the granular skeleton, increasing the continuity of macro voids. Despite these effects, the increases in water absorption remained relatively moderate due to the strong pore refinement ability of the ternary PLC–slag–silica fume binder. Slag’s late-age hydration significantly reduces capillary porosity, while silica fume eliminates micro voids in the ITZ. As a result, the mixtures maintained low permeability and remained suitable for pavement applications requiring long-term durability.



**Table 4.** Summary of results

Mixture	Compressive Strength (MPa)	Flexural Strength (MPa)	Splitting Tensile Strength (MPa)	Water Absorption (%)
RCC-Control	48–52	5.0–5.5	3.8–4.1	3.5–3.9
RCC-Rubber-3%	45–48	5.0–5.3	3.7–4.0	3.6–4.0
RCC-Rubber-5%	42–45	4.5–4.9	3.3–3.6	3.8–4.2
RCC-Rubber-8%	38–42	4.2–4.5	3.1–3.3	4.0–4.6

## 5. Conclusion

This study examined the fresh, mechanical, and durability performance of Roller-Compacted Concrete (RCC) produced with a ternary Portland-limestone cement (PLC) binder incorporating 40% slag and 7% silica fume, along with incremental additions of recycled tire rubber. The combined results demonstrate that both slag and rubber exert distinct and measurable influences on the behavior of RCC and that their interactions produce a balanced performance suitable for sustainable pavement applications.

The incorporation of high slag content played a central role in improving workability, pore refinement, and long-term strength development. Slag's finer particle size and smoother surface contributed to reduced inter particle friction, which, together with the ultrafine silica fume, produced a cohesive and compactable mixture even at very low water contents. The hydrating slag also generated additional calcium-silicate-hydrate (C–S–H) with a lower Ca/Si ratio, resulting in a denser microstructure and improved stress distribution throughout the hardened matrix. This densification helped mitigate the adverse effects introduced by rubber modification, particularly in maintaining structural integrity and permeability. The ternary PLC–slag–SF binder consistently delivered refined pore structure and low water absorption, confirming its suitability for low-carbon and durable RCC pavement systems. The introduction of recycled rubber produced predictable trends across fresh and hardened properties. In the fresh state, rubber acted as a deformable, low-density inclusion that reduced aggregate interlock and internal friction, leading to lower Vebe times and improved remolding under vibration. Even at higher rubber contents, mixture cohesiveness was preserved because the slag-rich paste offset the potential loss of internal cohesion typically associated with rubberized concrete. In the hardened state, rubber caused gradual and controlled reductions in compressive, flexural, and splitting tensile strengths due to its low stiffness, weak paste–rubber interfacial bonding, and disturbance of optimal particle packing. However, these strength reductions remained within acceptable limits for pavement-grade RCC up to 5% rubber, and even at 8% replacement levels the mixtures exceeded typical minimum compressive strength requirements. Rubber modification further imparted beneficial ductility, reduced brittleness, and enhanced energy absorption properties advantageous for pavement layers subjected to dynamic and impact loading [20-23].

Overall, the synergy between the PLC–slag–silica fume ternary binder and recycled rubber allows production of RCC mixtures that meet structural and durability expectations while advancing sustainability objectives. High slag content reduces clinker demand, suppresses early heat evolution, refines pore structure, and stabilizes mixture behavior, whereas rubber enables partial aggregate replacement with a waste-derived, resilient material that enhances ductility. The combined system achieves a practical balance between environmental performance and engineering functionality, demonstrating strong potential for low-carbon, high-performance RCC



pavement applications. Further investigation into long-term fatigue, freeze–thaw behavior, and field compaction characteristics would continue to expand the applicability of these sustainable RCC materials.

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