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Synergistic Effects of Recycled PET Particles and Silica Fume on the Fresh, Hardened and Durability Performance of Roller Compacted Concrete

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ABSTRACT

Roller Compacted Concrete (RCC) has garnered significant attention in the road and infrastructure sectors due to its economic and technical advantages. The integration of specific particles to bolster its strength without compromising workability is garnering increasing focus. This research provides an experimental assessment of the effects of polyethylene terephthalate (PET) particles — derived from recycled beverage bottles and plastic bags — and silica fume on the fresh and hardened properties of RCC. PET particle replacement by coarse aggregate was studied at increments of 0.5 to 2 % by volume or 5, 10, 15, and 20 kg per cubic meter. The fresh properties of RCC were evaluated using the Vebe consistency time test. Hardened characteristics were determined through measures like compressive strength, splitting tensile strength and flexural strength over varied durations. Additionally, water absorption and electrical resistivity tests were conducted to provide insights into durability. Initial results indicate an optimal PET particle concentration of 5 Kg/m^3 for balanced fresh and hardened RCC properties. Nonetheless, it's essential to highlight that a rise in PET particle dosage corresponded with a slight reduction in compressive strength. This investigation furnishes crucial perspectives for industry experts pursuing sustainable and efficacious enhancements for RCC applications.

Keywords: Roller-compactingconcrete, Fresh properties, Mechanical properties of concrete, recycled

1. INTRODUCTION

The global trend towards sustainable construction has been underscored by the escalating concerns regarding voluminous waste generated daily, exacerbated by the contemporary lifestyle, indiscriminate utilization of natural resources, and consequential environmental degradation adversely affecting all biota. A prominent contributor to this environmental quandary is the packaging industry, which predominantly relies on the polymer, polyethylene terephthalate (PET) for beverage containment. Over recent decades, there has been a marked upsurge in

PET bottle utilization, with reports indicating that in 2010, a staggering 265 million tons of plastic materials were produced globally [1] . Europe alone accounted for 57 million tons of this figure, and pertinently, 39% of this production was earmarked for packaging. Intriguingly, a juxtaposition of the manufacturing and recycling processes of these PET bottles reveals both to have significant environmental repercussions [2,3]. Building on this environmental context, the construction industry emerges as a prospective sector for PET waste repurposing. Specifically, Roller Compacted Concrete Pavement (RCCP) offers a potential medium for recycled PET incorporation to traditional concrete pavements due to its absence of dowels and steel reinforcement. Furthermore, the flexural strength of RCCP integrated with plastic/rubber/PET particles is comparable to, even superior to, conventional concrete pavements. Recent research underscores the growing appeal of RCCP due to its exemplary long-term performance coupled with minimized maintenance costs. Although RCCP is traditionally not the preferred option for high-speed traffic zones, there are emerging instances of its application in such areas. This rising interest in RCCP can be attributed to its inherent attributes, notably its fast construction process, and ecological advantages, including diminished vibrational noise and decreased labor congestion during placement. However, RCC's high viscosity and stability, a result of elevated filler material content, can make RCC more susceptible to early-age cracking from factors like plastic shrinkage and thermal stress than standard concrete. Recent research suggests that introducing plastic particles, such as PET, into concrete can increase its ductility, potentially mitigating this early-age cracking and reduced flowability of concrete mixtures. Given that RCC does not rely heavily on flowability – it is a zero-slump concrete – integrating PET particles, can be used without flowability concern. Moreover, the increasing use of PET in shape of fibers or particles in concrete structures has shown marked improvements in qualities like toughness, flexural strength, tensile strength, and impact resistance. With the global challenge of sustainably disposing of PET waste, especially in the form of bottles, innovative solutions are imperative. Traditional methods like incineration or burial can be ecologically detrimental. Current research is increasingly exploring the integration of plastic waste in mortar and concrete, with a particularly intriguing application being its use as a substitute for road pavement materials. Roller Compacted Concrete Pavement stands out in this regard. Beyond being cost-effective and rapidly deployable, RCCP is versatile, accommodating both with and without thin asphalt overlays. Given the large-scale deployment of RCCP worldwide, such as the 20,000,000 m^2 coverage in the United States in 2018 alone, the prospects for integrating recycled PET into this type of pavement have high potential. [4-8]

The incorporation of recycled PET in RCCP and similar concrete pavements promises myriad benefits. These range from efficient waste management and reduced carbon footprints to significant cost savings. Aggregates, forming between 65-80 vol% of concrete, crucially influence its core properties. Emerging research points to the promise of replacing these natural aggregates with recycled PET particles. Preliminary findings suggest such replacements can bolster concrete's toughness, flexural strength, and energy absorption - all vital for structures exposed to dynamic and impact loads. Additionally, PET-integrated concrete also showcases other advantages, like a decreased overall weight, increased permeability, and reduced water absorption, when compared to its conventional counterparts. In RCCP, both fine and coarse aggregates can comprise recycled materials. For instance, Modarres and Hosseini explored the impact of using Recycled Asphalt Pavement (RAP) — sourced from asphalt pavement repairs — as aggregates. Their findings suggested a decline in RCCP's compressive strength due to the inclusion of RAP. Nevertheless, given RAP's prevalence and the push for environmental conservation, its application has been advocated for low-traffic pavements. Additionally, Settari et al. assessed the mechanical and durability properties of RCCP, using varied RAP sizes as an aggregate replacement. Their findings showed that up to 50% replacement still ensured satisfactory pavement performance [9]. Courard et al. investigated the potential of incorporating recycled concrete into RCCP. After evaluating recycled aggregate properties such as Los Angeles (L.A.) abrasion, water absorption, and specific gravity, it was discerned that replacing natural aggregates with recycled ones caused a drop in RCCP's compressive strength. Nevertheless, RCC mixes with recycled aggregates still delivered decent results. The global rise in vehicle numbers has amplified tire production, highlighting the urgency for efficient tire and rubber recycling [10]. Fakhri and Saberi, proposed one such method: employing tier materials as RCCP aggregates. Several studies have explored different rubber particle sizes for RCCP [11]. Their collective findings indicate that rubber inclusion alters concrete properties, with most key metrics like elasticity modulus and various strengths experiencing a decline. However, certain benefits, including increased ductility, fatigue life, and reduced porosity and weight, were observed. Given the minimum strength guidelines for RCCP, plastic-inclusive pavements were deemed suitable for pedestrian zones and low-traffic roads. A limitation of rigid pavements is their limited flexibility, which can result in cracks. By introducing industrial waste like shredded plastic bottles as aggregates, the pavement's flexibility can be enhanced. Research conducted by Krishnamoorthy et al. underscored that incorporating between 10% to 30% of recycled plastic material can bolster specific properties of concrete pavements and concurrently result in cost benefits [12]. Silva et al. assessed the durability of concrete mixes that replaced natural aggregates with waste plastics (polyethylene terephthalate). Their results showed reduced durability for waste plastic-infused samples compared to the controls [13]. Ashwini also delved into the potential of E-plastic waste as an aggregate replacement. While this non-biodegradable material poses environmental challenges, using it in ratios of 10%, 20%, and 30% to replace aggregates showed varied results [14]. Notably, a 10% plastic inclusion enhanced the 28-day flexural strength and plasticity of the concrete.

In the realm of Roller Compacted Concrete (RCC) augmented with PET particles, the strategic introduction of silica fume can significantly boost various attributes. Silica fume, a by-product of ferrosilicon and silicon metal manufacturing, is distinguished by its elevated silicon dioxide (SiO2) content and ultra-fine spherical particle morphology [13] This unique configuration promotes superior capillary action and exhibits a robust pozzolanic reaction. These traits empower silica fume to refine the pore structure of the concrete, thereby optimizing its core properties [15]. Additionally, incorporating silica fume has proven to bolster both the tensile and compressive strengths of concrete while enhancing its resilience against frost [14,16]. It is essential to underscore the economic and environmental toll exacted by cement, an integral constituent of concrete. The production of a single ton of cement is responsible for emitting approximately 1 ton of carbon dioxide into the atmosphere [17]. Given these ramifications, there exists a compelling case for the partial replacement of cement with mineral additives bearing pozzolanic properties, like silica fume, especially within RCC formulations [18,19].

While previous research predominantly scrutinized the influence of PET particles or fibers on conventional concrete, the present exploration delves into the impact of PET particles on the fresh and hardened attributes of RCC. This investigation seeks to discern the feasibility of plastic particles as a synthetic aggregate in RCC pavements. The overarching goal is dual-faceted: mitigate the environmental footprint of discarded plastic bottles and curtail the rampant extraction of land resources essential for sourcing sand, gravel, and other aggregates for concrete. Nevertheless, reservations regarding the effective binding of PET particles within RCC have surfaced. To address these hesitations and enhance the microstructure and inherent properties of RCC, silica fume is introduced into the mix. Consequently, this research heralds dual eco-centric merits: a reduction in the use of natural aggregates and diminished cement consumption. Additionally, it aims to bolster the flexibility of concrete pavements—a common critique when compared with asphalt pavement—The incorporation of plastic particles seeks not only to alleviate these concerns but also to elevate the overall driving comfort.

2. MATERIALS AND METHODS

In this study, a benchmark RCC mixture was developed, replicating a real-scale RCC commonly employed in concrete plants for pavement applications. The primary components of this mixture were cement, silica fume, fine aggregate, and coarse aggregate. As part of the study's variation, shredded plastic bottles, sized between sieve No. 4 (4.75 mm) and sieve No. 1/2 (12.5 mm), were used to replace a portion of the coarse aggregate. The selected binder was Ordinary Portland Cement (OPC) Type II, with a density of 3.15 g/cm³ and a Blaine fineness of 400 m²/kg, as specified by ASTM C150 [20]. Additionally, amorphous silica fume, with a specific gravity of 2.2, was incorporated as per ASTM C1240 [21] standards. Table 1 provides the detailed chemical compositions of both the cement and the silica fume.

Table 1. Chemical characteristics of cement and silica fume

Chemical composition (%)	Cement	Silica fume
CaO	63.24	0.49
SiO_2	21.54	95.10
Al_2O_3	4.95	1.32
Fe_2O_3	3.82	0.87
MgO	1.55	0.97
SO_3	2.43	0.10
Na_2O	0.61	0.57
K_2O	0.30	0.35

In this study, both the fine and coarse aggregates conform to the ASTM C33 [22] standards. The fine aggregate is natural sand, chosen for its superior filler properties in the mix. The coarse aggregate consists of a blend of both natural and crushed sources. These coarse aggregates have a nominal maximum size of 19.5 mm and, in a saturated surface-dry (SSD) state, exhibit a specific gravity of 2590 kg/m³ and a water absorption rate of 1.5%. On the other hand, the fine aggregates (FA) present the SSD specific gravity of 2500 kg/m³ and a water absorption rate of 2.4%. The recycled Polyethylene Terephthalate (PET) utilized as an aggregate was sourced from discarded PET beverage bottles. These bottles were pulverized into granules using a shredding machine and then sieved to a size below 12.5 mm (1/2 inch). As a polymer, PET boasts a tensile modulus of elasticity of 2.9 GPa and a flexural modulus of elasticity of 2.4 GPa. Its peak tensile strength is approximately 60 MPa, accompanied by pronounced chemical resistance. The PET particles' specific gravity and water absorption are 1020 kg/m³ and 0.11%, respectively. Figure 1 visually represents the PET particles employed in this research.

Figure 1. PET particles used in this study

2.1. Mixture Proportions

This study incorporated a notable adjustment to the conventional RCC mix by substituting 10% of the ordinary Portland cement with silica fume. Regardless of this modification, a consistent water-to-cementitious material ratio (w/b) of 0.36 was maintained across all preparations. Each RCC mix had a combined powder composition (cement and silica fume) of 400 kg/m³. Additionally, the specified contents for coarse and fine aggregates for control mix were fixed at 800 kg/m³ and 1,016 kg/m³, respectively.

The creation of an RCC blend without the inclusion of PET particles, termed the 'Control mixture', was guided by the recommendations in ACI 327- Guide to Roller-Compacted Concrete Pavements [23]. For effective roller compaction and spreading, the RCC's consistency must be meticulously calibrated to prevent it from being overly rigid or excessively moist. Recognizing and setting the most suitable water-to-cementitious material ratio is thus crucial. Our finalized ratio emerged from keen observations of on-site roller compaction activities, leading to iterative adjustments in our mix design. The precise mixture components are detailed in Table 2.

Table 2. Mix proportions for roller-compacting concrete (kg/m^3).

Mix ID	Water (kg/m^3)	Cement (kg/m^3)	SF (kg/m^3)	CA (kg/m^3)	FA (kg/m^3)	PET (kg/m^3)	Total Unit Weigth (kg/m$^{3)}$
RCC-Ctrl	144	380	20	800	1016	-	2359
RCC-PET5	144	370	30	795	1016	5	2340
RCC-PET10	144	360	40	790	1016	10	2329
RCC-PET15	144	350	50	785	1016	15	2310
RCC-PET20	144	360	40	780	1016	20	228,0

2.2. Concrete Casting and Curing Procedure

PET particle quantities of 5, 10, 15, and 20 kg/m³, as detailed in Table 2, were incorporated into the control mixture. Subsequent investigations assessed the influence of these quantities on the fresh concrete's workability. Mixtures exhibiting desired fresh concrete characteristics were then subjected to hardened concrete tests. Consistency in the mixing procedure and duration is paramount, due to importance of moisture-loss in RCC. Therefore, all concrete mixtures followed a uniform mixing process. Emulating the real-world RCC mixing process of a batching plant, aggregates were first blended in the mixer for 3 minutes. Subsequently, cement and silica fume were introduced, and dry mixing continued for an additional 3 minutes. Roughly 60% of the mixing water was then incorporated, ensuring thorough mixing for 2 minutes. Prescribed PET particle quantities were gradually introduced to the active mixer, ensuring a uniform blend after 2 minute of mixing. Finally, the remaining water was added, with the mix blending for another 3 minutes. The Vebe consistency of the resulting mixtures was gauged as a workability indicator, and specimens were molded accordingly. Tests were aligned with the ASTM C1170 [24] Standard Test Method for gauging the consistency and density of RCC via a vibrating table. Relevant workability thresholds, as advocated by ACI 211.3R [25], are delineated in Table 3.

Table 3. Workability of zero slump concrete

Consistency Description	Slump (mm)	Vebe (s)
Extremely Dry	-	35 to18
Very Stiff	-	18 to 10
Stiff	0 to 25	10 to 5
Stiff Plastic	25 to 75	5 to 3
Plastic	75 to 125	3 to 0
Very Plastic	125 to 190	-

Hardened phase evaluations encompassed compressive strength, splitting tensile strength, and flexural strength tests. For compressive strength, three 150 mm cubes were tested at curing periods of 3, 7, 28, and 90 days, consistent with ASTM C39 [26], applying a loading rate of 0.25 MPa/s. Splitting tensile strength evaluations utilized three 150x300 mm cylinders over curing durations of 3, 7, 28, and 90 days, adhering to ASTM C496 [27], at a 1.2 MPa/s loading rate. Flexural strength tests were conducted on three 150x150x600 mm prismatic specimens at 28 and 90 days, in line with ASTM C293 [28], with a 1 MPa/min loading rate. Additionally, water absorbtion tests at 28 days followed ASTM C 1585 [29], and surface resistivity assessments at intervals of 28 and 90 days conformed to AASHTO T358 [30]. To bolster result accuracy and account for potential variances, three samples were tested at each specified age. During the curing process, RCC samples were placed in a moisture room maintained at 25±2 °C with 95% humidity for the initial 24 hours. Following this, samples were demolded and treated with a curing compound before being covered with wet tarps, replicating the real-world RCC curing situation commonly observed in the field. This setup was sustained for a duration of 7 days. After the 7-day period, samples were carefully removed from the tarps and transitioned to a laboratory setting. There, they were conditioned at a temperature of 23±3 °C and 70% humidity, where they remained until their specified testing age arrived.

3. RESULTS AND DISCUSSION

3.1. Fresh concrete results

The fresh properties of Roller-Compacted Concrete (RCC) mixtures were assessed using specific apparatus and procedures. One of the crucial apparatus for this assessment is the Vebe consistometer, which comprises a cylindrical container, a slump cone, a transparent disc, and a vibrating table. (Figure 2)

Figure 2. Tests on fresh roller-compacted concretes

Additionally, a stopwatch or timer is necessary to record the time. To conduct the test, the slump cone is placed inside the cylindrical container. The concrete sample is then filled into the cone in three equal layers. Each layer is tamped 25 times using a tamping rod to ensure proper filling and removal of air pockets. After filling, the slump cone is carefully removed, and the concrete sample is covered with the transparent disc. The vibrating table is then activated, initiating the compaction process of the concrete sample. As the concrete undergoes compaction, the transparent disc gradually descends. The time taken from the start of the vibration until the transparent disc fully contacts the surface of the concrete, and a touch of wetness or sheen becomes visible surrounding the disc, is diligently observed. This visible wetness or sheen indicates that the concrete has compacted entirely. This duration is termed the "Vebe time." The Vebe time serves as an indicator of the workability of the concrete. In the context of zero-slump concrete, a shorter Vebe time is suggestive of better workability, providing valuable insights, especially when other methods like the traditional slump test may not be as effective. The results clearly indicated a negative correlation between the content of PET particles and workability: as the particle content increased, the workability diminished. Specifically, the PET15 and PET20 mixtures exhibited unsatisfactory viscosity levels. This decline in workability, as revealed by extended Vebe consistency time tests, suggests the production of a less flowable concrete primarily due to PET inclusion.

Several factors contribute to this observed reduction in workability. Firstly, the shape and surface texture of the PET particles play a pivotal role. These particles tend to clump together, adversely impacting the rheological properties of the mix. The planar configuration of PET particles not only facilitates congestion among the concrete components but also disrupts the concrete matrix by introducing high air content. This phenomenon results in a porous concrete structure. Additionally, unlike natural aggregates that can absorb water, PET, being a polymer, remains impermeable. When introduced into the concrete, PET particles displace water that would otherwise be instrumental in the mix, leading to decreased workability. If one increases the percentage of PET without making corresponding adjustments to other mix ingredients, such as water or admixtures, the decline in workability becomes even more pronounced. In standard concrete mixtures, a common solution to this reduction in workability due to PET particles is the introduction of superplasticizers. These chemicals enhance the workability without compromising the concrete's strength or durability. However, this remedy is not straightforward for RCCs, which are characterized by zero-slump concrete. Overuse of superplasticizers can render the RCC excessively flowable – a trait that is undesirable and often avoided. Thus, in RCC formulations, the addition of superplasticizers is typically rare and not recommended.

While all mixtures showed almost an acceptable Vebe consistency (Table 4), those with a 5% and 10% replacement of waste PET particles demonstrated only a minor decline in workability parameters. These particular mixtures, especially in terms of Vebe time, fall within a more desirable and acceptable range of Vebe time.

Table 4. Fresh concrete test results

Mix ID	Vebe consistency time (sec)
RCC-Ctrl	15
RCC-PET5	18
RCC-PET10	22
RCC-PET15	30
RCC-PET20	38

3.2. Hardened concrete results

Although the incorporation of pet particles can potentially contribute to sustainable construction practices, it is vital to understand how PET affects the mechanical behavior of the resulting composite. Generally, the inclusion of PET particles modifies various mechanical properties, such as compressive strength, tensile strength, and elasticity, primarily due to the inherent physical characteristics of PET and its interaction with the cementitious matrix.

3.2.1. Compressive strength

The compressive strength test was carried out using a compression testing machine with a capacity of 3000 kN, as depicted in Figure 3. The results are graphically presented in Figure 4. A clear observation from the data is that the compressive strength of all mixtures improved with the aging of the concrete. Nevertheless, the introduction of waste PET particles led to a marginal decrease in strength across all ages, becoming more pronounced with higher PET percentages. Specifically, at 28 days, the incorporation of 5% PET fiber resulted in a 4% decrease in compressive strength. This reduction was more significant with 10%, 15%, and 20% PET replacements, witnessing decreases of 11%, 21%, and 31% respectively. This diminished strength can be attributed to a couple of factors. Firstly, the adhesion between the waste PET particles and the cement paste is possibly weaker than that of traditional aggregates with the paste. Moreover, PET particles inherently possess a lower modulus of elasticity compared to conventional aggregates. When subjected to compression, these particles tend to deform more readily, compromising the overall strength of the composite. This phenomenon, combined with a potentially weaker interfacial transition zone (ITZ), can result in reduced cohesion in the mix, subsequently affecting its workability.

Figure3. Compressive strength specimen and test machine

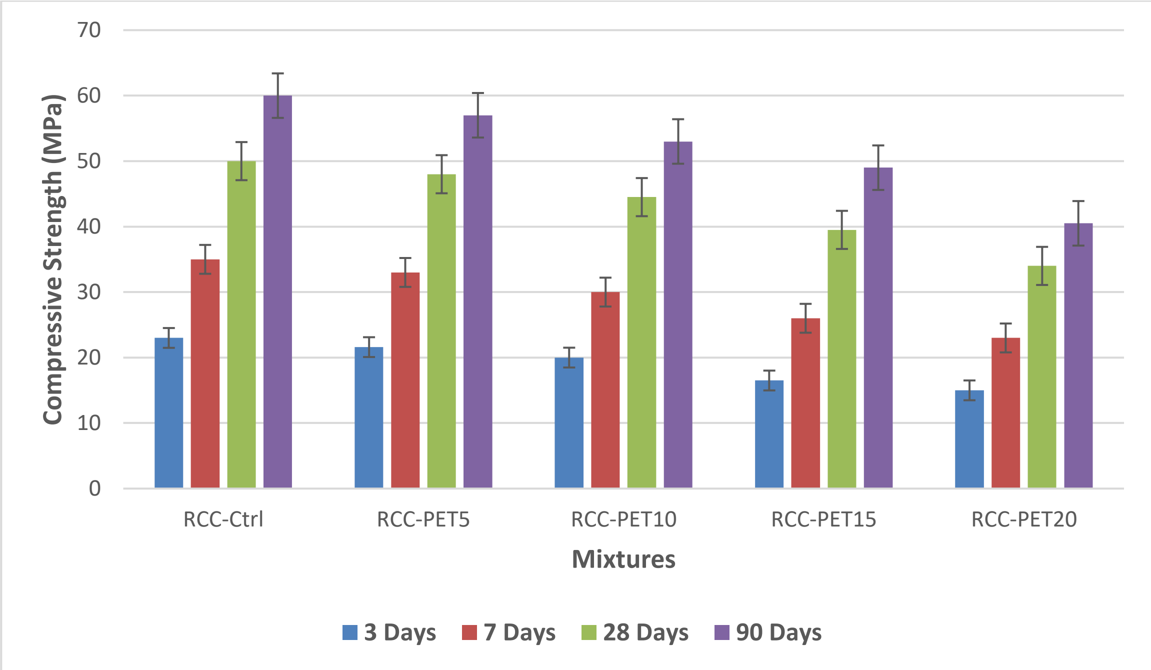

Figure 4. Compressive strength of control and PET containing mixtures

In all ages, the most important observation during testing was the change of the failure mode of the concrete as the PET particles were included in RCC. The failure mode changed from sudden failure into a more ductile failure. This due to the strong bond between PETparticles and the concrete, and the effect of this plastic particles in preventing concrete from sudden explosive failure.

3.2.2. Splitting tensile strength

The test configurations for the tensile test is illustrated in Figure 5, with corresponding results presented in Figure 6. Notably, concrete mixtures reinforced with PET particles exhibited an enhanced splitting tensile strength, registering an increase of 6% to 13% over ages spanning 3 to 90 days compared to the control concrete. These mixtures demonstrated increased flexibility and reduced brittleness, attributes that became more pronounced with higher PET particle inclusion. Such enhancement in plasticity, which is beneficial for concrete pavements, can be attributed to the replacement of coarse aggregate with larger PET particles. These particles likely lodge within the matrix, functioning as bridging particles during tensile stresses, analogous to the behavior of wide fibers.

Figure 5. Splitting tensile specimen and test apparatus

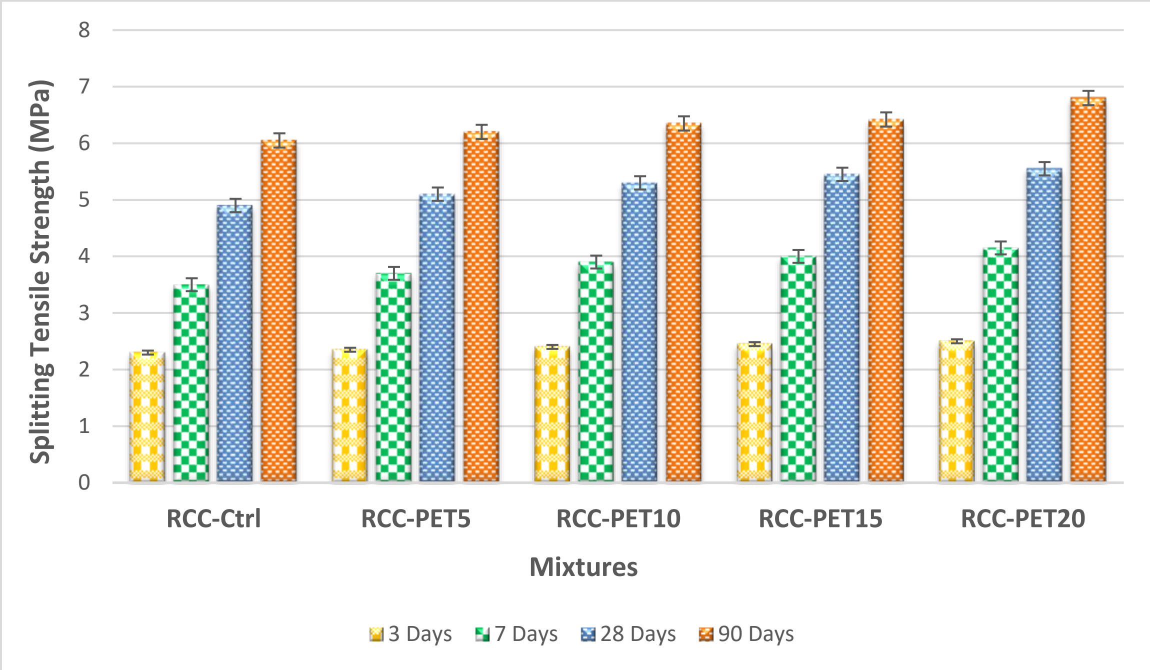

Figure 6. splitting tensile strength of control and PET containing mixtures

Figure 7 further elucidates the relationship between the splitting tensile strength and cylindrical compressive strength of RCC mixtures. The tensile strength values for mixtures with 5, 10, and 15 kg/m^3 PET particles align with the recommended range by the CEB-FIP (2010) code for low slump concrete.

Supporting this observation, other literature studies [31-34] indicate that while larger PET particles enhance tensile performance by acting as pseudo-fibers, finer PET particles diminish tensile strength, lacking the bridging capability of their larger counterparts.

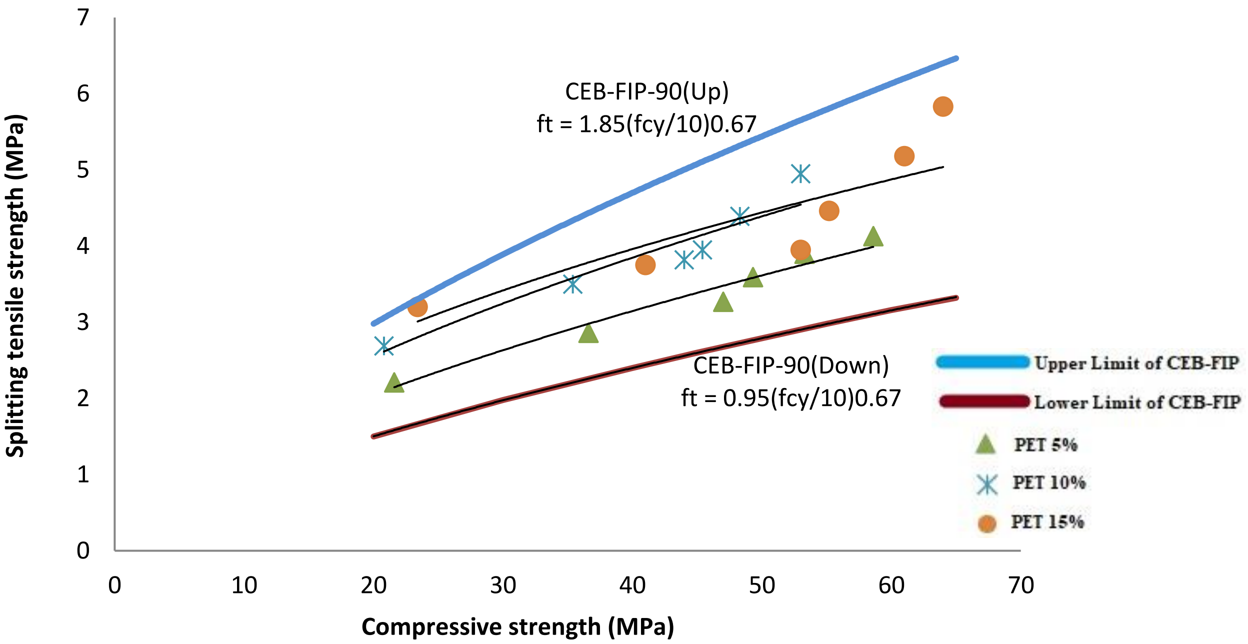

Figure 7. Variation splitting tensile strength vs. compressive strength

3.2.3 Flexural strength

Flexural strength tests, in line with ASTM C293, were conducted on prismatic beam specimens at 28 and 90 days, with the equipment and results depicted in Figures 8 and 9, respectively. Our findings highlight the efficacy of waste PET aggregates in enhancing the flexural strength of RCC mixes. When PET is introduced into the mix, these particles are embedded within the matrix, functioning similarly to wide fibers by acting as bridging particles during tensile stresses. Specifically, at 28 days, a mix containing 0.5% PET replacement showed a 10% increase in flexural strength. The strength further improved for mixes with PET ratios of 1%, 1.5%, and 2.0%, registering increments of 14.6%, 18%, and 21% respectively. This demonstrates the synergistic effect of Silica Fume and the bridging capability of PET particles in bolstering the flexural attributes of the RCC mix.

Figure 8. Flexural strength test setup

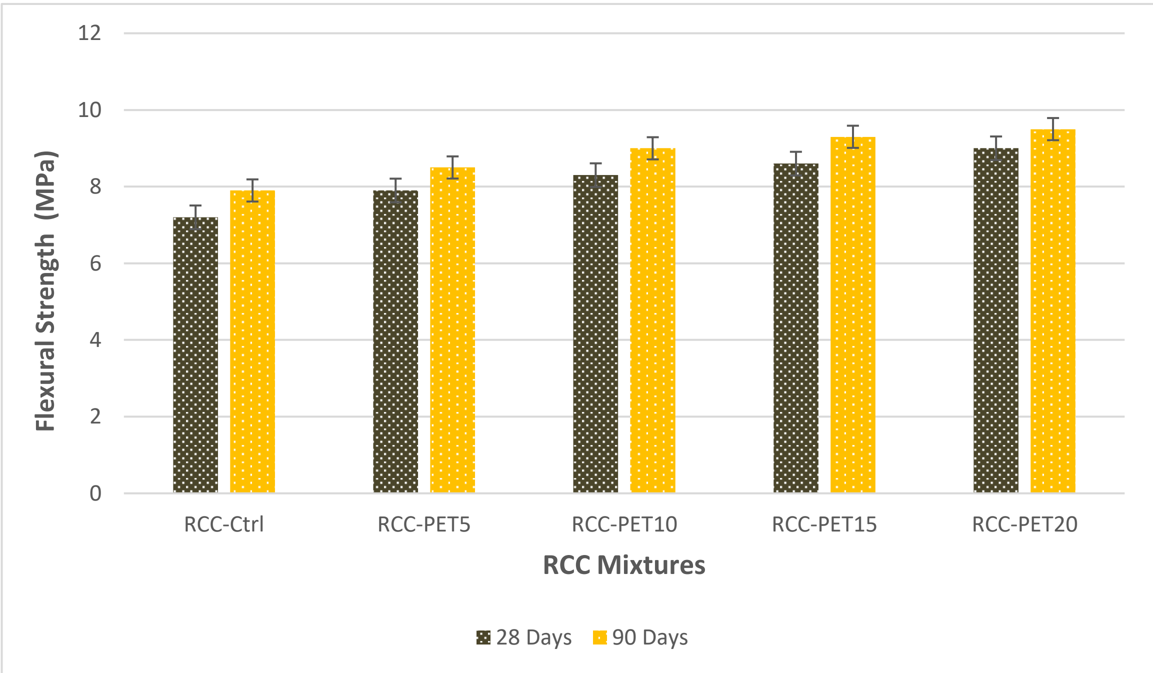

Figure 9. Flexural strength of all mixtures

Furthermore, the inclusion of PET particles in RCC notably modified the failure behavior. Contrary to the abrupt, explosive failures typically observed in ordinary concrete mixtures, RCC mixes with PET exhibited a more ductile failure. Impressively, the specimens did not split entirely into two distinct halves upon failure, suggesting the enhanced cohesion brought about by PET inclusions. A visual representation of the fractured surfaces for various specimens under mechanical tests is provided in Figure 10.

Figure10. Failure mode after mechanical tests

3.3. Durability Results

Long-lasting concrete pavements, which can withstand the infiltration of corrosive chemicals, are crucial in infrastructure construction. A key parameter for enhancing durability is minimizing porosity, an aspect we examined through water absorption tests based on ASTM C 1585 for RCC specimens aged 28 days. The findings, summarized in Table 5, highlight that the inclusion of PET particles in RCC results in a marginal increase in water absorption rates. This uptick in absorption is attributed to the planar shape of PET particles and the restricted hydration of cement in PET-inclusive mixes. Conversely, the presence of silica fume tends to mitigate water absorption, suggesting that when combined with PET, a compensatory effect occurs regarding water absorption properties. It's worth noting that due to the low density of PET particles, an increase in PET concentration leads to a reduction in the overall density of the concrete. As the density reduces, water absorption values of mixes containing PET rise. Thus, integrating pozzolanic materials can refine the microstructure of RCC, countering the impact of PET additions.

Table 5. Water absorbtion of RCC Mixtures

Mix ID	Water absorption (%)
RCC-Ctrl	3.8
RCC-PET5	4.0
RCC-PET10	4.4
RCC-PET15	5.4
RCC-PET20	6.9

The durability of RCC mixtures, especially in terms of their vulnerability to the transport of aggressive ions, was assessed through electrical resistivity tests. Essentially, the electrical resistivity of concrete offers insights into its microstructural properties, especially the distribution and interconnectivity of its pores. A more interconnected pore system translates to enhanced electrical current flow, thereby diminishing resistivity. Interestingly, our findings show that while increasing the PET content in the mix, the electrical resistance of the samples remains unaffected, leading to decreased capillary suction and absorption. This phenomenon can be attributed to the lower water/cement ratio found in RCC mixtures combined with the presence of silica fume. The addition of silica fume not only enhances the microstructure of the specimens but further refines the pore network.

Referring to Figure 11, it is evident that the electrical resistivity remains almost consistent with the increased substitution of PET particles, particularly evident at 90 days. A deeper dive suggests that a higher concentration of micro silica culminates in a more compact cementitious matrix, consequently reducing the ingress of harmful agents. Moreover, the potent pozzolanic activity of silica fume leads to the formation of additional C-S-H gel, effectively blocking micro-transport channels. Collectively, these effects are the main contributors to the consistent electrical resistivity of the RCC mixes, rather than the inclusion of PET.

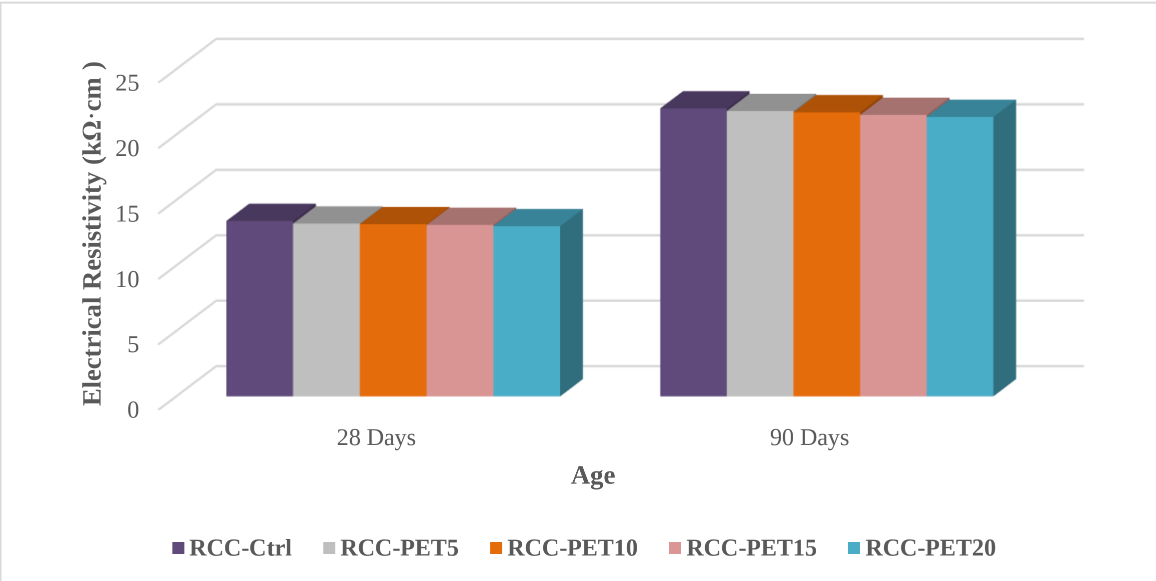

Figure 11. Electrical resistance results

4. CONCLUSION

This research delved into the impact of repurposed waste particles from plastic bottles (PET) on the fresh, hardened, and durability attributes of RCC. A compelling drive for this investigation was the potential environmental advantages of utilizing these waste materials, echoing sustainable development tenets. Based on the findings, the following conclusions are drawn:

- The construction sector can repurpose a significant volume of PET waste, mitigating environmental concerns. Recycled PET has found applications such as polymer concrete resins or being transformed into polyester fibers. Notably, our study accentuates that PET particles, when merely pulverized (undergoing physical changes rather than energy-intensive recycling), can be effectively incorporated into concrete, especially in roller-compacted concrete (RCC). To put this into perspective, over 800 waste bottles are needed to generate 10 kilograms of PET particles for every cubic meter of concrete, presenting a viable strategy for waste management and sustainable development.
- In terms of fresh concrete attributes, a dosage of 5 kg/m^3 of PET particles emerge as the optimal inclusion rate for RCC blends. Incorporating more than 10 kg/m^3 of PET in RCC is not advisable. Our tests revealed that additions beyond this threshold, notably 15 kg/m^3 and 20 kg/m^3, compromise workability, evident from the Vebe consistency time test results,

thus posing challenges during roller compaction.

- While PET's inclusion mildly compromises the RCC's compressive strength, this reduction remains minimal up to 10 kg/m^3. However, a 20 kg/m^3 dosage results in a significant 30% drop. This can be attributed to the weak bond between the cement paste and PET particles. To counteract this, the integration of silica fume is advisable, especially in mixes containing plastic particles.
- RCC mixes with waste PET particles outperform control concrete in split tensile strength across all examined ages, with enhancements reaching up to 13% at 90 days.
- PET inclusion bolsters the RCC's flexural strength by approximately 20% at both 28 and 90 days, making them superior to control mixes. Such improvements underscore the potential of PET particles in enhancing pavement performance under traffic loads.
- PET particles in RCC enhance the material's fracture toughness, ensuring that even after fracturing, the concrete segments remain interconnected. This feature is invaluable, particularly when considering impact or explosive forces.
- PET additions generally reduce the density of all mixes, attributable to PET's lower specific gravity. Despite its influence on compressive strength, higher PET dosages could pave the way for lightweight concrete solutions. For instance, a 20 kg/m^3 addition reduced concrete's unit weight by nearly 5% without causing significant disruptions in mechanical properties.
- While higher PET content slightly elevates water absorption, it doesn't substantially alter the RCC's electrical resistivity. Notably, the incorporation of silica fume markedly enhances the mix's electrical resistance.

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