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Mechanical and Microstructural Properties of Environmentally Friendly Concrete Partially Replacing Aggregates with Recycled Rubber and Recycled PET

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Abstract

Today, waste generation is a worldwide problem, where the major source of waste is generated by worn-out tires and Polyethylene Terephthalate (PET) bottles. Therefore, as a way to provide an ecological disposal and reduce the environmental impact, the feasibility of producing ecological concrete (EC) with recycled rubber (RB) and PET as substitutes for natural aggregates is explored, determining their physical, mechanical and microstructural properties. This experimental study considered the replacement of fine aggregate with RB at 1%, 4%, 7%, 10%, 20% and 30%, and the optimum content of coarse aggregate plus the replacement of coarse aggregate with PET at 1%, 5%, 10% and 15%. The results showed that the optimum percentage of RB was 1%, which, when combined with PET, resulted that the design with 1% RB+ 1% PET was the optimum replacement combination, increasing 10% in bending, 1% in compression and for tension it decreased by 11%, in turn with the XRD test quartz and different aluminosilicates were found, such as portlandite and by SEM-EDS it was possible to visualize polymer flakes embedded in the analyzed fragment. It is concluded that RB and PET can be viable for the production of EC only if low percentages of replacement by natural aggregates are used.

Keywords: rubber; ecological concrete; mechanical and microstructural properties; PET.

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Introduction

In the construction sector, concrete is the most widely applied material worldwide, and consists of fine sand as fine aggregate, and gravel from quarries is used as coarse aggregate, cement, water and optionally admixtures (Mahesh Kumar et al., 2019). Nowadays the application of waste and recycled aggregates in concrete mixes is attracting attention in order to treat and use solid waste and thus to have an ecological concrete (EC) (Atif et al., 2020).

The use of ~~CE~~ EC is one of the sustainable construction approaches introduced in the industry, which can reduce environmental problems (Szpetulski et al., 2022), PET is used in large quantities for bottling products, such as bottles for mineral water and other consumer goods (Islam, 2022; Saxena et al., 2020; Shahidan et al., 2018). It is also considered a product in high demand, as an average of 10 million plastic bags are discarded in developed countries such as the capital of India (Saxena et al., 2020), in Malaysia, an Asian country, PET production exceeds 6.7 million tons/year (Shahidan et al., 2018).

It should be noted that the inputs used for concrete production have slightly increased, as well as the increasing acceleration of urbanization has led to an increase in the amount of solid waste (Zhao et al., 2022). On the other hand, another waste of greater abundance is tires accumulating approximately 75 million abandoned tires annually (Pongsopha et al., 2022), in the case of New South Wales, Australia, 1.5 billion tires are produced every year (Karunarathna et al., 2021); and only 10% of them are recycled, due to their three-dimensional cross-linked structure, which makes them non-biodegradable (Atef et al., 2021), which is considered a negative factor for the environment, since all landfills where they were stored are becoming unacceptable (Nakhai and Alhumoud, 2020).

Several literatures show studies on the use of rubber and PET in concrete mixes. According to, Gerges et al. (2018) explored the effect of the use of recycled rubber as aggregate fine (FA) for concrete mixtures, determining that, at 28 days, the reduction in compressive strength is from an average of 30%, to 63%, also in tensile there was a decrease in strength, thus being 5% RB, the rate that has a lower decrease in strength with respect to the other percentages. This agrees with, (Ayub et al., 2021; Shaaban et al., 2021), which established that the optimum percentages to use are 5 to 10 % RB. According to (Habib et al., 2020) it should be less than 15% RB when replaced by FA. According to, (Fauzan et al., 2021) indicated that workability decreases with the increase of RB, so they recommended the use of a maximum RB content of 10%. (Mohammed and Breesem, 2022) observed that RB produced a decrease in slump from 4 cm to 2.6 cm for 0% and 30%, for compressive strength it did not show significant changes with 10%, the opposite occurred with 30% RB which decreased 9.8%, and there was also decrease in tensile and flexural strength, being 10% the optimal replacement percentage.

On the other hand, Bachtiar et al. (2020), asserted that PET fibers have a positive impact on the workability of concrete, as long as they are in low percentages. They recommended the use of 25% PET, as it causes a lesser decrease in strength compared to other analyzed percentages, a theme echoed in other studies. Additionally, Irmawaty et al. (2020) observed that with 10%, the target slump value of 8 ± 2 cm is achieved. However, adding more PET makes the concrete rigid and challenging to work with, also decreasing the unit weight. In terms of compression and tension, with 10% PET, the strength was drastically reduced by 21.23% and 17.8%, respectively, compared to conventional concrete. Similarly, in bending, there was a reduction in strength, demonstrating that the substitution of PET plastic should be limited to 10% of the volume of coarse aggregate (CA). Likewise, Saxena et al. (2020) mentioned the optimal dosage as 5% PET. This aligns with the statements of (Kamaliah and Handayani, 2021), suggesting that PET bottles can be used in concrete mixtures, but only if the amount of PET does not exceed 5% replacement of CA.

In relation to the microstructural properties of concrete, (Agrawal et al., 2023) identified the phase composition of materials for concrete with 10% and 15% recycled concrete aggregates (RB) through EDS analysis. Meanwhile, Oluwaseun et al. (2019) conducted EDS analysis, revealing that in the mixture with 1% RB, there is a presence of 8.28% Oxygen, while with the other designs, there is a higher presence of oxygen. At 10% RB as a replacement for FA, the oxygen content was recorded at

33.70% (Guo et al., 2019). Furthermore, Kumar and Dev (2022) carried out XRD analysis for concrete with 10% up to 30% RB as a replacement for FA, indicating that all mixtures exhibited a crystalline nature. Additionally, the presence of silicon oxide, calcium carbonate, carbon sulfide, sulfur, calcium, and sodium was found in almost all analyzed concrete samples. Concerning concrete containing 100% PET, it shows a high percentage of Ca and minor amounts of O, C, Au, Al, Si, Mg, and Na. On the other hand, concrete with 20% PET indicated high amounts of Si, O, and Ca, along with moderate amounts of Al, Au, Na, and Mg in the selected areas (Bamigboye et al., 2022a).

Therefore, this work is carried out with the objective of determining the physical, mechanical and microstructural properties of ecological concrete, exploring the feasibility of using recycled tire and bottle materials as partial substitutes for natural aggregates, thus providing a form of ecological disposal and reducing the environmental impact caused by the production of industrial fibers.

Methods and Materials

Cement

Type I cement was used for this study, in accordance with ASTM C150 (ASTM International, 2007). The specific gravity of the cement is 3.10 g/cm^3.

Table 1

Physical properties of aggregates

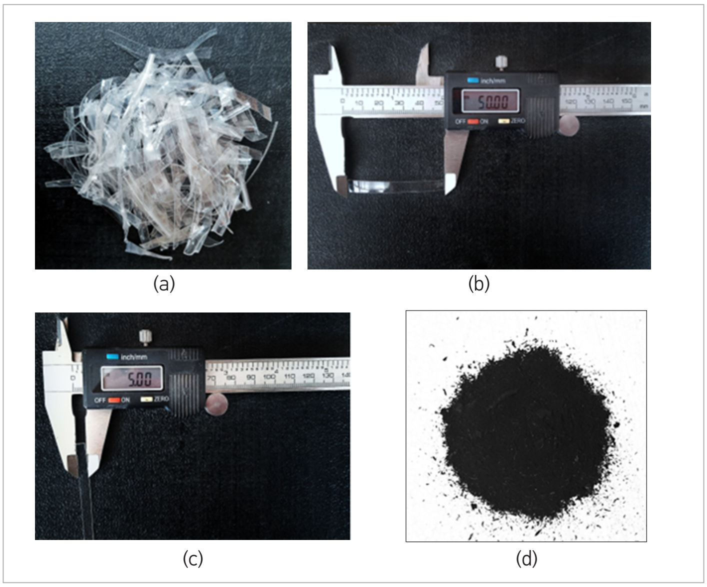
Properties	FA	CA
Specific gravity (g/cm^3)	2.65	2.72
Absorption (%)	1.28	0.94
Modulus of fineness	3.09	3.02
Moisture content (%)	0.70	0.28

Aggregates

Fine aggregate was used with a maximum size of 4.75 mm and coarse aggregate with a maximum size of 20 mm, both quarries located in Lambayeque, Peru. It should be noted that the aggregates were obtained according to the specifications of ASTM D 75 (ASTM International, 2014) and their properties are detailed in Table 1.

Fig. 1

Inputs used (a) Recycled PET fibers, (b) Length of PET fiber-50mm, (c) Width


(a) (b)
(c) (d)

Recycled rubber and PET

The RB used for the present experimental work was obtained from the mechanical pulverization of tires with a size fraction of 1 mm and the PET from the collection of bottles, which were subjected to a process of washing, drying and manual cutting, obtaining rectangular fibers of 1 mm (thickness) x 5 mm (width) x 50 mm (length). Both inputs are shown in Fig. 1 and their properties are detailed in Table 2.

Table 2

Characteristics of recycled rubber and PET

No.	Parameters	Values
	Rubber	
1	Density (g/cm^3)	1.19
2	Moisture content (%)	2.02
3	Modulus of fineness	3.41
	PET recycled	
1	Density (g/cm^3)	1.25
2	Tensile strength (kg/cm^2)	2679

Water

Potable water from the laboratory was used for the production of concrete and the curing process of the concrete specimens.

Mixing, emptying and curing

For the preparation of the in-situ concrete, the ACI 211 method (ACI Committe 211, 1997) was adopted; all concrete mixtures were made in a laboratory mixer with a capacity of 11 cubic feet, with a constant water/cement (w/c) ratio and without superplasticizer. The fresh concrete was placed in cylindrical plastic molds and prismatic molds. The molds used were oiled to fill with fresh concrete under the compaction of 25 strokes with a rod every 3 layers, the physical properties of the concrete were evaluated, as shown in **Table 3**.

Table 3

Fresh concrete testing

No	Testing	Standards
1	Slump	ASTM C 143 (ASTM International, 2012)
2	Air Content	ASTM C 231 (ASTM International, 2014)
3	Temperature	ASTM C 1064 (ASTM International, 2011)
4	Unit weight	ASTM C 138 (ASTM International, 2014)

A total of 330 specimens were produced of which cylindrical specimens were 231 and prismatic specimens were 99, made with three different manufacturing procedures: A: conventional concrete mix, B: concrete mix with rubber and C: concrete mix with optimal dosage of rubber and PET. The curing process was performed after 24 hours where the fresh concrete mixtures were achieved to set to a hardened state, each specimen was demolded and placed in potable water poses under submersion with ASTM C31 (ASTM International, 2019) procedures cured until the date of the tests, where the compressive, flexural and tensile strength tests were evaluated at 7, 14 and 28 days, respectively.

The compressive strength was realized according to ASTM C39 (ASTM International, 2014), and cylindrical specimens of 150 x 300 mm, were used, and a 2000 kN capacity compressive strength testing machine was used for loading. Tensile tests were carried out according to ASTM C 496 (ASTM International, 1996) and flexural tests according to ASTM C78 (ASTM International, 2002), and the specimen sizes were 100 x 200 mm cylinders and 150 x 150 x 500 mm beams, respectively.

Once process A, consisting of conventional concrete (CC), was completed, process B, consisting of concrete with rubber (CRB), was carried out, for which FA was replaced by different percentages of RB, these being 1%, 4%, 7%, 10%, 20% and 30% by volume of the same, where cylinders and beams were tested, thus determining the optimum rubber content corresponding to the maximum compressive strength. The design of the mixtures of processes A and B are shown in **Table 4**.

For process C, CA was replaced by recycled PET fibers, in percentages of 1%, 5%, 10% and 15% with respect to the volume of CA, plus the substitution of FA by the optimum percentage of RB determined in process B. The rest of the procedure is the same, since the optimum content of concrete with PET (CPET) and RB was determined based on the maximum compressive strength, so the mix design per cubic meter of process C is shown in **Table 5**.

Table 4

Design of mixture process A and B with relation w/c 0.72

Designs	Materials				
	Cement (Kg/m^3)	CA (Kg/m^3)	FA (Kg/m^3)	Water (L)	RB (Kg/m^3)
CC	352	876	867	254	0
CRB1	352	876	860	254	6.7
CRB4	352	876	834	254	27
CRB7	352	876	808	254	47
CRB10	352	876	782	254	67
CRB20	352	876	695	254	134
CRB30	352	876	608	254	202

Table 5

Design of mixture process C with relation w/c 0.72

Designs	Materials					
	Cement (Kg/m^3)	CA (Kg/m^3)	FA (Kg/m^3)	Water (L)	RB (Kg/m^3)	PET (Kg/m^3)
CRB1 + CPET1	352	866	860	254	6.7	4.0
CRB1 + CPET5	352	831	860	254	6.7	20.1
CRB1 + CPET10	352	787	860	254	6.7	40.2
CRB1 + CPET15	352	744	860	254	6.7	60.2

Once the optimum design of concrete with recycled rubber and PET was identified, the crystalline phases were analyzed by X-ray diffraction (XRD), as well as morphological and compositional analysis by scanning electron microscopy (SEM) in conjunction with energy dispersive X-ray spectroscopy (EDS). A total of two samples were submitted, one for each technique.

X-Ray Diffraction (XRD)

X-ray diffraction analysis was performed with Bruker DRX equipment model D8 Discover with copper radiation ($Cu_{K\alpha}$ = 0.15418 nm), 40 mA current and 40 kV accelerating voltage, with a Lynx-eye detector with energy selectivity. The analysis was performed in a range of angles (2θ) from 15° to 70° in steps of 0.02°. The time per step was 1 s. To calculate the composition of the crystalline phases and the amorphous part, the Reference Intensity Ratio (RIR) method was applied. The minimum concentration for this method is 0.1 wt%.

Scanning Electron Microscopy (SEM) and EDS characterization

Measurements were performed with an FEI Quanta 200 model scanning electron microscope (SEM), for which an accelerating voltage of 30 kV and a spot size of 6 were used for both imaging and compositing. Areas were measured at magnifications of 100x and 500x, depending on the image characteristics. Energy dispersive X-ray spectroscopy (EDS) measurements were performed with an EDAX detector mounted on the microscope. Data processing and elemental composition determination were performed with EDAX Genesis XM 4 software, using a ZAF matrix correction. As for sample preparation, fragments with features of interest were selected and mounted on aluminum electron microscopy poles with carbon adhesive tape and fixed with copper tape. All samples were coated with a thin layer of 20-40 nm gold to make their surface conductive and facilitate high vacuum imaging. The presence of gold was deliberately excluded from the EDS compositional analysis to avoid confusion.

Thus, the summary of the processes under study is shown in **Fig. 2**.

Fig. 2

Process flow diagram

Results and Discussion

The analysis of results was carried out based on the data obtained from the laboratory tests, with the purpose of analyzing the effect of the percentage of RB and recycled PET fibers in the concrete. In this sense, the results for fresh and hardened concrete of CC, CRB and CRB+CPET are detailed.

Physical properties of CC and CRB

The replacement of FA by RB increases, the slump decreases. In this sense, when the CC has a slump of 10.16 cm, its consistency is said to be plastic and workable; on the other hand, the concrete with 30% RB, having a slump of 5.84 cm, its consistency is dry and not workable, is shown in Fig. 3. In turn (Fauzan et al., 2021), indicated that workability tends to decrease with a high content of RB, since with 10% and 20% of this input, a reduction of 40.00% and 71.43%, respectively. Aligning with Mohammed and Breesem (2022), as they detailed that, replacing RB at 0%, 10%, 20% and 30% led to a decrease in settlement obtaining values of 4 cm, 3.2 cm, 2.8 cm and 2.6 cm respectively18, thus according to both authors, they determined that settlement is inversely proportional to the quantity of RB added, which is in agreement with the study carried out.

The CRB30 has a higher trapped air content, since compared to CC there is an increase of 3%, and it can be seen that the higher the percentage of RB, the higher the trapped air, is shown in Table 6. The opposite is true for the unit weight, which tends to decrease as the percentage of RB increases, which is why the unit weight of CRB30 decreases 129.8 kg/m^3 compared to CC, agreeing with (Pongsopha et al., 2022) as they detailed that the unit weight of concrete decreased with the increase of RB and arose because this input has a lower specific gravity than FA. Finally, the temperature obtained shows that all are within the established range, since none exceeds 32 °C, established by NTP E060 (Ministerio de Vivienda Construcción y Saneamiento , 2009).

CRB30 has a higher trapped air content, since compared to CC there is an increase of 3%, due to increased doses of RB, because the greater the trapped air and the appearance of internal pores. Reflecting in the fresh unit weight, which tends to decrease as the percentage of RB increases, that is why the unit weight of CRB30 decreases to 129.8 kg/m^3 compared to CC, coinciding with (Pongsopha et al., 2022) as they detailed that the unit weight of concrete decreased with the increase of RB and arose because this input has a lower specific gravity than fine aggregate. Finally, the temperature obtained shows insignificant oscillations since all the samples are within the established range, since none exceeds 32 °C, established by NTP E060 (Ministerio de Vivienda Construcción y Saneamiento , 2009), the physical properties tests can be observed in Table. 6.

Fig. 3

Settlement values of CC and CRB

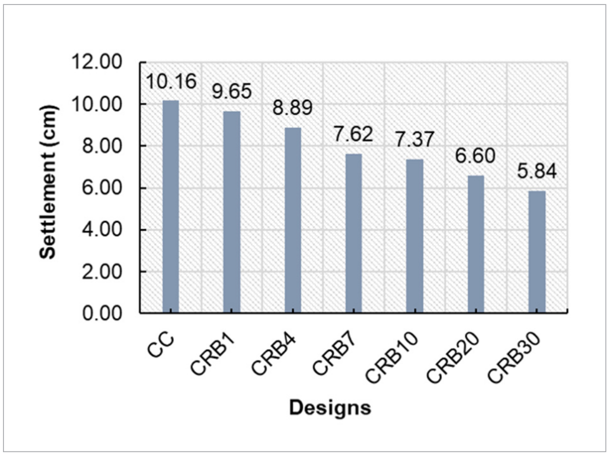


Table 6

Physical properties of CC and CRB

Designs	Air content (%)	Unit weight (Kg/m^3)	Temperature (°C)
CC	1.30	2327.51	28.00
CRB1	2.70	2311.17	29.00
CRB4	3.50	2265.62	25.20
CRB7	3.90	2230.09	25.00
CRB10	4.10	2219.34	24.60
CRB20	4.20	2215.47	24.00
CRB30	4.25	2197.71	23.25

Mechanical properties of CC and CRB

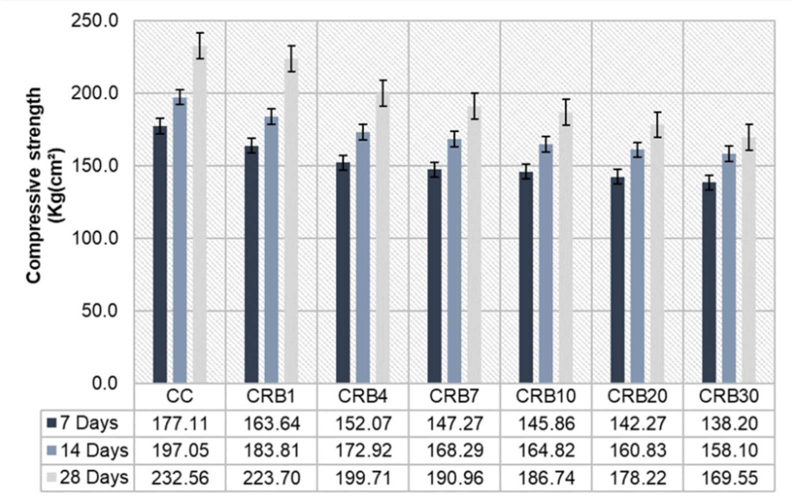
Compressive strength

The results showed that the compressive strength of the concrete with 1% RB, at 28 days reached a strength of 223.70 kg/cm^2, which was lower than that of the CC, but was higher than the strength for which it was designed (210 kg/cm^2), in this sense the decrease with respect to the CC is 8.86 kg/cm^2. Likewise, on day 28, the compressive strength of the concrete with 4%, 7%, 10%, 20% and 30% RB had a lower strength than that for which it was initially designed, as well as the CC sample decreasing by 32.85 kg/cm^2, 41.59 kg/cm^2, 45.81 kg/cm^2, 54.34 kg/cm^2 and 63.01 kg/cm^2 respectively.

In fact, an unusual behavior was observed on the resistance and its variations of increase with higher doses, as in the case of sample CRB10, and then a decrease in resistance with sample CRB20, may be due to the random way in which the RB was placed, and to the density of this material, unlike the fine aggregate, as shown in **Fig. 4**.

Fig. 4

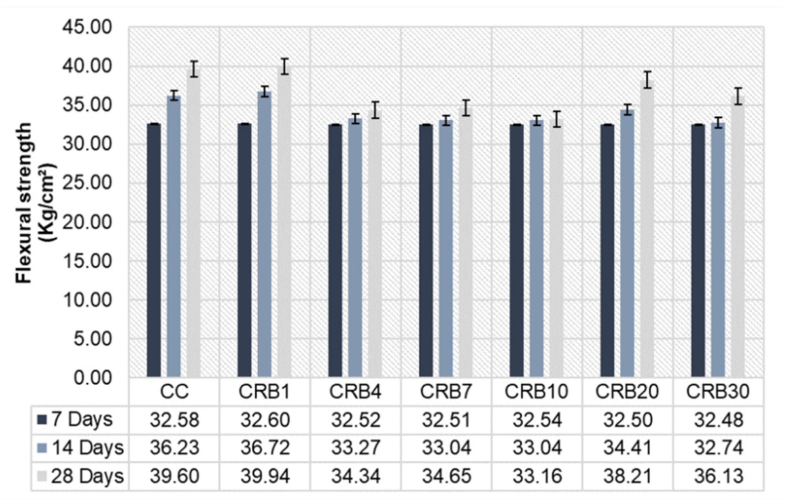
Compressive strength of CC and CRB



In comparison with the results obtained, according to (Aureliano et al., 2019) mentioned that at 28 days the resistance had a drop of 80% in compressive strength. Mohammed and Breesem (2022) mentioned that the compressive strength presented significant changes with 30% RB, decreasing 9.8% with respect to the control mix. (Shaaban et al., 2021) indicated that the partial substitution of FA with ground RB reduced the compressive strength to different degrees depending on the percentage provided recommending that the RB content should be limited to 10% for structural applications. According to (Pongsopha et al., 2022) mentioned that due to the lower strength of ground RB compared to that of fine aggregates, in such sense by replacing strong materials with weak materials, the strength gradually decreases. This is due, according to (Fauzan et al., 2021) to a lack of adequate bonding between the rubber particles and the cement, in addition to the lower stiffness of the substitute material.

Flexural strength

The results of flexural strength at the age of 28 days, CRB1 presented a strength of 39.94 kg/cm^2, which when compared to CC, showed a slight increase of 0.34 kg/cm^2, for CRB4 had a decrease of 5.27 kg/cm^2 and CRB7 also showed a decrease compared to CC, decreasing by 4.95 kg/cm^2. On the other hand, CRB10, CRB20 and CRB30 showed a tendency to decrease by 6.44 kg/cm^2, 1.39 kg/cm^2 and 3.47 kg/cm^2, respectively in reference to CC, as shown in **Fig. 5**.



	CC	CRB1	CRB4	CRB7	CRB10	CRB20	CRB30
■ 7 Days	32.58	32.60	32.52	32.51	32.54	32.50	32.48
■ 14 Days	36.23	36.72	33.27	33.04	33.04	34.41	32.74
■ 28 Days	39.60	39.94	34.34	34.65	33.16	38.21	36.13

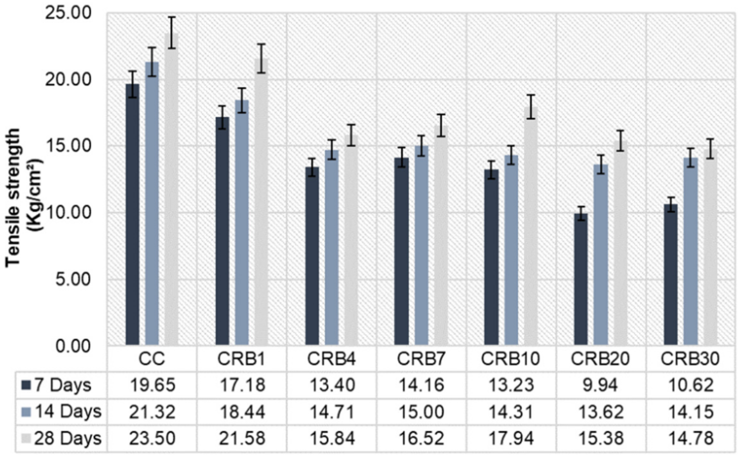
Fig. 5

Flexural strength of CC and CRB

Shaaban et al. (2021) specified that the RB content resulted in a lower maximum load, since they observed that cracking occurred before failure at the maximum load, at the same time they stated that with 10% RB a resistance 22.60% higher than the control sample was obtained. Not agreeing with this research since, with this percentage of substitution, the resistance decreased up to 16%. On the contrary, the results of (Ayub et al., 2021) determined that there was a decrease in strength with increasing RB, inferring that with 5% to 10% RB as a substitute for FA is adequate in for modulus of rupture, since with 10% RB the strength decreased by 18%. This observation agrees with the results obtained in this study, since with 10% the strength decreased by close percentages. Similarly, Mohammed and Breesem (2022) observed that with the same percentage substitution a smaller decrease in strength was achieved compared to the other percentages. Consequently, both authors detail that the higher the percentage of rubber substituted, the lower the flexural strength. Furthermore, according to the values obtained, only the CRB1 design is superior to the CC design.

Tensile strength

The results of tensile strength at 28 days, the CRB1 sample presented a strength of 21.58 kg/cm^2, which in comparison with the CC decreased by 1.92 kg/cm^2, CRB4 had a decrease of 7.66 kg/cm^2 and CRB7 decreased by 6.99 kg/cm^2. For their part, CRB10, CRB20 and CRB30 had a tendency to decrease by 5.56 kg/cm^2, 8.12 kg/cm^2 and 8.72 kg/cm^2, all in reference to CC, as shown in **Fig. 6**.



	CC	CRB1	CRB4	CRB7	CRB10	CRB20	CRB30
■ 7 Days	19.65	17.18	13.40	14.16	13.23	9.94	10.62
■ 14 Days	21.32	18.44	14.71	15.00	14.31	13.62	14.15
■ 28 Days	23.50	21.58	15.84	16.52	17.94	15.38	14.78

Fig. 6

Tensile strength of CC and CRB

From the values obtained, agreement is shown with s they determined that similar to the case of compressive strength, it was also found that concrete decreases with increasing RB content, so also (Gerges et al., 2018) at 28 days observed that the tensile strength decreases with varying percentage of RB replacement, in turn showed more cohesive behavior that fails without splitting. About the decrease in strength (Fauzan et al., 2021) posited that the reasons may be due to the weak bond between cement pastes and RB, therefore, the interface zone between rubber and cement may act as a micro-crack that accelerates the decomposition of concrete. Similarly, Ayub et al. (2021) detailed that with 5%, 10%, 15% and 20% CA the resistance was reduced by 10.75%, 21.5%, 53.4% and 36.6% respectively; this is in agreement with Mohammed and Breesem (2022), since they demonstrated that with similar replacement percentages the tensile strength decreases significantly. In this sense, the present research agrees with all the aforementioned authors, since they detail that the content of RB in concrete tends to decrease its strength. On the other hand, Shaaban et al. (2021) observed that the resistance with 10% RB, obtained a 21% higher resistance in reference to the control sample, being in disagreement with the results obtained since with this percentage the resistance decreased by 24% based on the CC.

Physical properties such as CC and CRB+CPET

Once it was determined that the optimum percentage of RB as a substitute for FA was 1%, the mix design was carried out and its physical properties were determined.

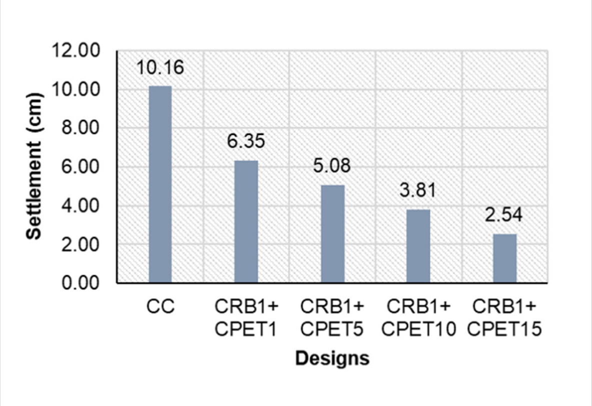
The settlement (slump) results it was observed that as the substitution of CA for PET increases the slump decreases, it should be noted that according to ASTM C 143, the target range is 7.62 cm to 10.16 cm (3”-4”), as shown in **Fig. 7**, in this sense, when there is a slump of 2.54 cm and less, it is said that the consistency of the concrete is dry and not very workable, this decrease is due to the presence of PET fibers in the concrete causes greater friction between the particles.

According to, Bachtiar et al. (2020) determined that the higher the percentage of replacement of CA by plastic waste, the higher the value of slump test; according to with (Bamigboye et al., 2022b) showed that there is a progressive increase in slump with increasing percentages of PET, agreeing with (Islam, 2022; Lee et al., 2019) showed that with increasing PET content, slump values increase almost proportionally. Likewise, (Saxena et al., 2020) detailed that the shape of PET particles influenced the decrease in workability, as they were not uniform. However, (Irmawaty et al., 2020) detailed that at 10% the target slump value of 8 ± 2 cm is still met. Contrary to the results of this study, since with this percentage a settlement of 3.81 cm was obtained, being out of the target range.

The air content test, in fresh concrete mixes with 15% PET had a higher trapped air content, since in comparison with the CC it had an increase of 2.3%, concluding that the higher the percentage of PET, the higher the percentage of trapped air. Consequently, the increase in the percentage of PET was reflected in a decrease in the unit weight, this arose because PET is a material that has a low density and the random way in which it was placed in the preparation of the mixture created voids between the inert materials, reason why the unit weight of CRB1 + CPET15, decreased up to 300.3 kg/m^3 compared to CC, as shown in **Table. 7**.

Fig. 7

Settlement values of CC and CRB + CPET



Agreeing with (Irmawaty et al., 2020) detailed that the unit weight decreased the higher the percentage of PET substitution by CC, as well as with (Islam,

Table 7

Physical properties of CC and CRB+CPET

Designs	Air content (%)	Unit weight (Kg/m3)	Temperature (°C)
CC	1.30	2327.51	28.00
CRB1 + CPET1	2.00	2315.47	32.00
CRB1 + CPET5	2.15	2302.29	31.00
CRB1 + CPET10	2.50	2291.55	28.00
CRB1 + CPET15	3.50	2027.22	27.00

2022) where demonstrated that the unit weight decreases with the increase of plastic aggregate content and the increase of w/c ratio. Finally, the temperature obtained shows that all of them are within the established range, since none of them exceeds 32 °C, as established by NTE E060 (Ministerio de Vivienda Construcción y Saneamiento, 2009).

Mechanical properties of CC and CRB+CPET

Compressive strength

The results of the compressive strength of the CRB1 + CPET1 design, at 28 days reached a strength of 211.62 kg/cm^2, being lower than that of the CC design, but higher than the strength for which it was designed of 210 kg/cm^2, in this sense the decrease with respect to the CC design was 20.93 kg/cm^2. Likewise, at day 28, the concrete with 5%, 10% and 15% PET had a lower strength than that for which it was initially designed, as well as lower than that of the CC design, decreasing by 42.25 kg/cm^2, 56.97 kg/cm^2 and 74.14 kg/cm^2 respectively, as shown in **Fig. 8**.

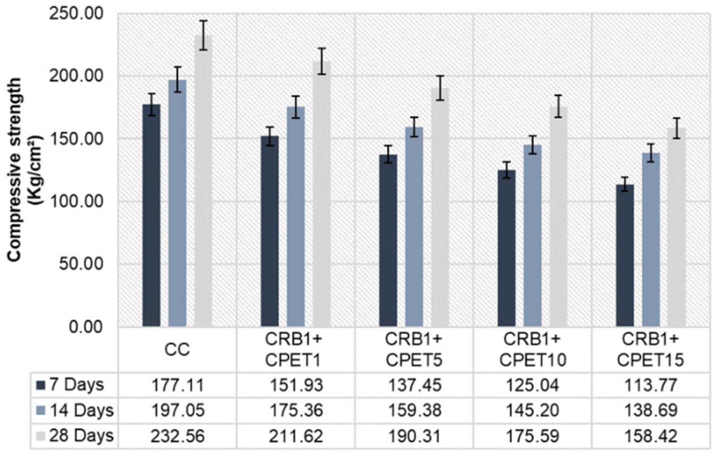


Fig. 8

Compressive strength of CC and CRB+CPET

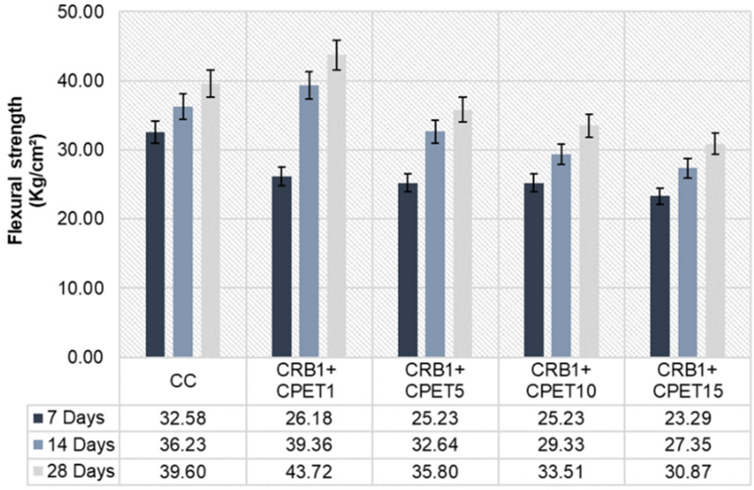
In comparison with the results obtained, the one demonstrated by (Bachtiar et al., 2020; Bamigboye et al., 2022b; Kamaliah and Handayani, 2021) aligns with this research because they determined that the relationships between the percentage of PET artificial aggregate and the compressive strength of concrete are very significant, the higher the addition of PET, the lower the strength , this in turn aligns with (Irmawaty et al., 2020) since they evaluated that with 10% PET the resistance was drastically reduced by 21.23% with respect to the CC, and further specified that the reduction was due to the fact that PET did not act in the same way as crushed stone. Similarly, (Islam, 2022) detailed that all concrete variations showed a pattern of decreasing compressive strength with increasing w/c ratio, and further detailed that the reduction in strength was especially due to the smooth surface of the PET aggregate. (Saxena et al., 2020) expressed that the decrease in strength can be attributed to the fact that the PET aggregate cannot interact with the cement paste. Thus, all authors agree that the PET content decreased the compressive strength, with the exception of (Lee et al., 2019) since they detailed that for replacements of 10% PET there were strengths higher than the minimum compressive strength required for structural concrete, being used in structural applications, as long as the replacement percentage is less than 30%. Disagreeing with the values obtained in this research, since with only 10% PET the concrete does not comply with the resistance for which it was designed, being only the CRB1 + CPET1 design the one that complies with this resistance.

Flexural strength

The results of the flexural strength at the age of 28 days, the CRB1+CPET1 design presented a strength of 43.72 kg/cm^2, which when compared to the CC design, showed an increase of 4.11 kg/cm^2; however, for the CRB1+ CPET5 design, it presented a decrease of 3.8 kg/cm^2. On the other hand, CRB1 + CPET10, and CRB1+ CPET15, had a decrease of 6.09 kg/cm^2 and 8.73 kg/cm^2 respectively, all this decrease refers to the CC design, as shown in **Fig. 9**.

Fig. 9

Flexural strength of CC and CRB+CPET



	CC	CRB1+ CPET1	CRB1+ CPET5	CRB1+ CPET10	CRB1+ CPET15
■ 7 Days	32.58	26.18	25.23	25.23	23.29
■ 14 Days	36.23	39.36	32.64	29.33	27.35
■ 28 Days	39.60	43.72	35.80	33.51	30.87

From the values obtained shows agreement with (Bachtiar et al., 2020; Irmawaty et al., 2020) observed that the effect of the percentage of PET plastic waste on the value of the flexural strength of concrete, had a significant influence indicating that the higher the percentage of PET plastic waste, the lower was the flexural strength of concrete, just as (Saxena et al., 2020) considered 5%, 10%, 15% and 20% PET as a substitute for CA demonstrating a decrease in strength, in turn states that it could have been due to the decrease in adhesive strength between the surface of the waste PET particles and the cement paste, as well as the hydrophobic nature of waste PET, which sometimes limits the hydration of cement. Consequently, according to the authors and the research conducted, there is a similarity in that the use of PET as a substitute for FA causes a decrease in strength, indicating that the result of the CRB1 + CPET1 design increased flexural strength.

Tensile strength

The tensile strength at 28 days the CRB1 + CPET1 design, presented a strength of 21.11 kg/cm^2, which when compared to the CC design decreased 2.57 kg/cm^2, the CRB1 + CPET5 design in turn had a reduction of 4, 78 kg/cm^2 and CRB1 + CPET10 with CRB1 + CPET15 also decreased drastically, with a reduction of 5.82 kg/cm^2 and 6.03 kg/cm^2 respectively, all in reference to the CC design, as shown in **Fig. 10**.

Thus, the results obtained agree with (Irmawaty et al., 2020) as they showed a decrease in tensile strength with increasing PET volume in concrete. Also, Islam (2022) detailed that the tensile

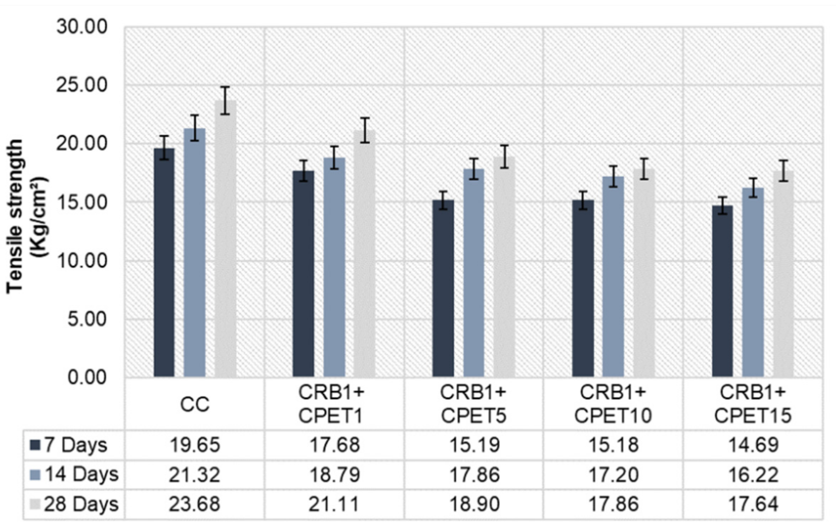


Fig. 10

Tensile strength of CC and CRB+CPET

strength seems to decrease with increasing w/c ratio. On the contrary, there is no agreement with (Bamigboye et al., 2022a) since they determined that with 10% and 20% PET they reached substantial values, being slightly higher than the control sample, as well as (Bamigboye et al., 2022b) detailed that with 20% PET the highest tensile strength was achieved among the modified mixes being this the optimal replacement percentage. Considering what was mentioned by both authors is the opposite of the present investigation, since all the percentages used for this study had a decrease in the concrete strength, being the CRB1+ CPET1 design, which presented a lower decrease.

X-ray Diffraction

The XRD results of the concrete with 1% PET as replacement of the coarse aggregate and 1% RB as replacement of the fine aggregate are presented, thus the main crystalline components of this concrete can be seen in **Table 8**, where the concentration (wt%) of quartz is 43.1%, anorthite 17.0%, orthoclast 11.0%, portlandite 2.4%, cristobalite 1.7% and the amorphous crystalline phase 24.8%, is shown in **Fig. 11**.

These results are similar to those of the research conducted by Kumar and Dev (2022), the results showed that in the concrete with RB analyzed there was the presence of SiO_2 in high concentrations, as the mixtures had mostly crystalline silicon oxide, thus it was identified that crystalline quartz is significantly less reactive, i.e., it will not react under normal conditions and will only react at a very high temperature, which is beneficial for concrete with RB, The concrete with 1% RB and

Table 8

Concentration of crystalline phases in the sample

Crystalline phase	Formule	According to # of the database	Concentration (wt%)
Quartz	SiO_2	46-1045	43.1
Anorthite	$CaAl_2Si_2O_8$	70-0287	17.0
Orthoclase	$KAlSi_3O_8$	71-0957	11.0
Portlandite	$Ca(OH)_2$	44-1481	2.4
Cristobalite	SiO_2	75-0923	1.7
Amorphous	---	---	24.8

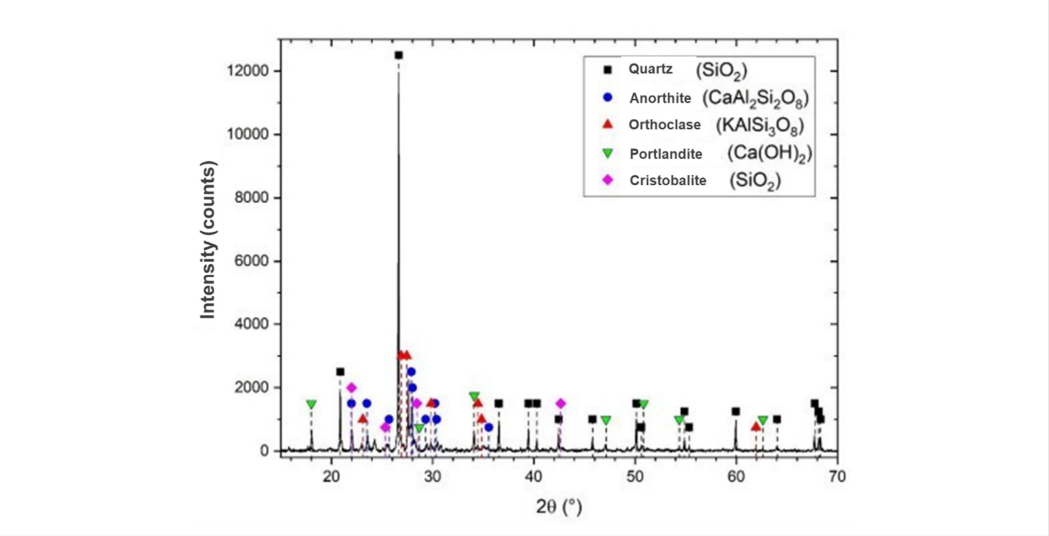


Fig 11

X-ray diffractogram of the sample and the crystalline phases identified

1% PET had the highest concentration of quartz at 43.1%, and lower values of different components, in addition to the presence of an amorphous crystalline phase at 24.8%.

Scanning Electron Microscopy (SEM) and EDS characterization

The SEM images were considered to maximize the information that can be appreciated visually in the SEM images, we chose to show combined images that superimpose the backscattered electron detector signals with the secondary electron detector signals in a single image. In this way, both morphological (secondary) and compositional (backscattered) features could be appreciated. The 100x micrograph shows a polymer flake embedded in the hardened concrete fragment, as seen in Fig. 12.

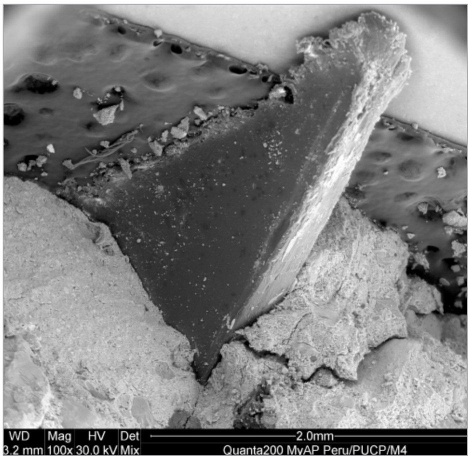


Fig 12

100x micrograph of adhesion available with rubber and PET (SEM)

SEM images were obtained to characterize the concrete, where another image was taken at a magnification higher than 500x, where some regions of interest have been highlighted, as seen in Fig. 13. In particular, a pore (green arrow) can be observed, as well as one of several crystalline type features (P1), and the base material (P2). The results of the EDS elemental analysis of P1, P2, and the total image area show observed features that are in agreement with the results of the XRD analysis. In particular, a calcium-rich region was observed in P1, as shown in Table 9.

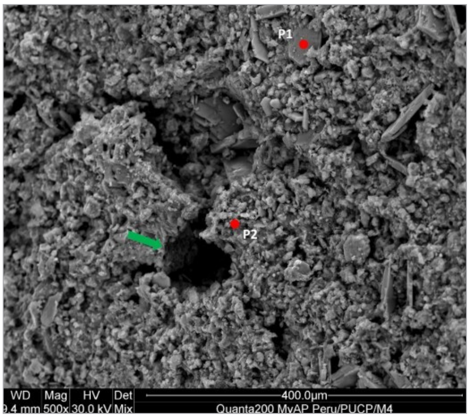


Fig 13

500x micrograph with some regions of interest highlighted of the adhesion available with rubber and PET

These results showed similarity with those detailed by (Agrawal et al., 2023) in concrete with RB identified the presence of Ca, O, Si, in similar atomic weight percentages. (Oluwaseun et al., 2019) observed the presence of 19.44% C, 8.28% O, 0.63% Si, 49% Fe, 14.04 Cl and 7.05 Ni, coinciding with the results of this study, since there

Table 9

Composition control by EDS in several regions of interest of the sample

Chemical element	Total area		P1		P2	
	wt%	at%	wt%	at%	wt%	at%
C	13.36	23.27	---	---	---	---
O	36.84	48.17	---	---	43.89	63.07
Mg	0.64	0.55	---	---	1.42	1.34
Al	3.21	2.49	---	---	4.20	3.58
Si	9.25	6.89	---	---	13.54	11.08
S	---	----	---	---	1.32	0.95
K	1.04	0.55	---	---	0.94	0.55
Ca	31.97	16.69	100.00	100.00	31.81	18.24
Fe	3.69	1.38	---	---	2.88	1.18

was also presence of these chemical elements. Similarly, (Guo et al., 2019) observed that concrete with CA contained C in 25.68%, O (33.70%), Si (10.74%), Al (2.59%) and K (3.95%), being values very close to those of this study. In turn (Bamigboye et al., 2022a) revealed that concrete with PET indicated high amounts of Si, O and Ca, and moderate amounts of Al, Au, Na and Mg, having an alignment with this research since these chemical elements were also present.

Conclusions

This study investigated the effect of RB and PET as replacement agents for concrete aggregates and the physical, mechanical and microstructural properties, reaching the following conclusions:

1. Variations in the workability, unit weight and air content of concrete are influenced by the amount of substitution of recycled aggregates by RB and PET, where the higher the percentage of substitution, the lower the values obtained for its physical properties.
2. The ratios between the percentages of RB and PET recycled aggregates influence lower strength at higher aggregate substitution in compressive, tensile and flexural strength tests at 7, 14 and 28 days.
3. It was shown that the optimal use of RB at 1% had improvements with respect to the design control strength 210 kg/cm^2, as it increased up to 6.52%, 10.94% and 2.76% corresponding to compressive, flexural and tensile strength at 28 days of curing. However, at higher doses there was no significant improvement in the mechanical properties of the concrete.
4. It was shown that the optimum use of RB+PET at 1% had improvements over the design control strength 210 kg/cm^2, as it increased up to 0.77%, 21.44% and 0.52% corresponding to compressive, flexural and tensile strength at 28 days of curing. However, with respect to the strength of conventional concrete, there was no significant improvement, but it was within the minimum normative parameters.
5. From the XRD analysis, it was found mostly quartz and different aluminosilicates, as well as portlandite, in both cases there is a percentage of amorphous material that cannot be identified with XRD, also by SEM it was possible to visualize one of the polymer flakes embedded in the analyzed fragment and in turn, elements consistent with the XRD results were observed.
6. Ecological concrete made with RB and PET can be incorporated up to 1% for both waste residues, being used for both structural and non-structural elements of simple concrete; likewise, from an environmental analysis, its reuse is very favorable for reducing environmental pollution and favoring the Sustainable Development Goals in the face of climate change.

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