

Mechanical behavior of sustainable concrete; case study of low substitutions of fine plastic as aggregate

Comportamiento mecánico de concreto sustentable; caso de estudio sustituciones bajas de plástico fino como agregado

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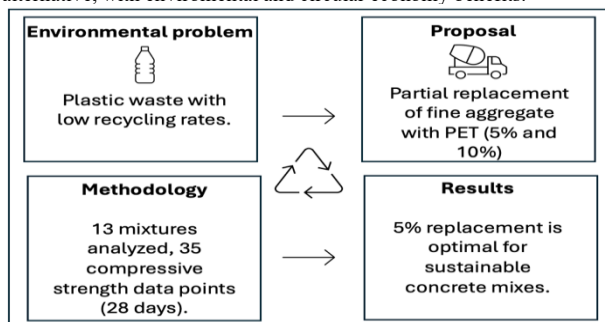
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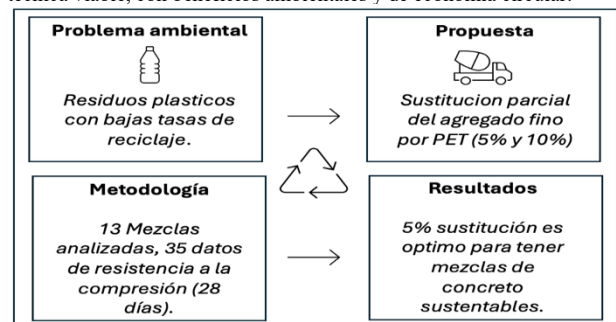
Abstract

This study analyzes the mechanical behavior of sustainable concrete when incorporating recycled polyethylene terephthalate [PET] as a partial replacement for fine aggregate. Articles reporting mixtures with 5% and 10% replacements were reviewed. A total of thirteen mixtures and thirty-five 28-day compressive strength data points were collected and compared with control mixtures. The statistical analysis included measures of central tendency, dispersion, and percentage variation, which allowed for the normalization of result between different studies. The findings show that the 5% replacement has an average variation of -2.6%, indicating a minimal impact on strength, while the 10% replacement reports an average reduction of -11.9%. Although variability was observed, fine-grained PET favored compactness and mechanical performance. These results consolidate 5% as a viable technical alternative, with environmental and circular economy benefits.



Resumen

Este estudio analiza el comportamiento mecánico del concreto sustentable al incorporar tereftalato de polietileno reciclado [PET] como sustitución parcial del agregado fino. Se revisaron artículos que reportan mezclas con reemplazos de 5% y 10%. En total se recopilieron trece mezclas y treinta y cinco datos de resistencia a la compresión a 28 días, comparados con mezclas control. El análisis estadístico incluyó medidas de tendencia central, dispersión y variación porcentual, lo que permitió normalizar resultados entre diferentes estudios. Los hallazgos muestran que el 5% de sustitución presenta una variación promedio de -2.6%, indicando un impacto mínimo en la resistencia, mientras que el 10% reporta una reducción media de -11.9%. Aunque se observó variabilidad, el PET de granulometría fina favoreció la compactación y el desempeño mecánico. Estos resultados consolidan al 5% como una alternativa técnica viable, con beneficios ambientales y de economía circular.



Sustainable Concrete, Recycled PET, Polyethylene Terephthalate, Mechanical Properties.

Concreto sustentable, PET Reciclado, Tereftalato de Polietileno, Propiedades Mecánica

Area: Advocacy and attention to national problems

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Introduction

In recent decades, the increase in plastic waste has been a global concern due to its low biodegradability, excessive accumulation in landfills, and negative impact on terrestrial and marine ecosystems. It is estimated that since the 1950s, more than 8.3 billion tons of plastic have been produced, of which about 79% has ended up in landfills or scattered in the environment [Geyer et al., 2017]. Polyethylene terephthalate [PET] is commonly used in the production of bottles and packaging. It is also the most widely produced polymer and the least reused, which has led to the search for strategies for its incorporation into construction materials such as hydraulic concrete.

Concrete is the most widely used material in the world after water [Mehta & Monteiro, 2014]. It is used in most infrastructure, and its intensive production involves large volumes of non-renewable raw materials such as sand, gravel, and cement, which generate a significant environmental impact, mainly in terms of CO₂ emissions and depletion of natural resources [Habert et al., 2020]. As a result, the construction industry has begun to adopt more sustainable practices aimed at reusing waste in the production of concrete with recycled aggregates [Pacheco-Torgal et al., 2013]

Currently, the environmental problem caused by plastic waste is one of the main global challenges. It is estimated that approximately 300 million tons of plastic waste are generated each year, of which only 9% is recycled [Ocampo & Santa Catarina, 2019]. This low recycling rate poses a serious environmental risk, as this waste occupies a considerable volume and remains in the environment for decades.

In Mexico, the same study reports that 1,951,785 kg of plastic waste is generated daily, a significant amount that could be used in various recycling applications, such as the sustainable construction sector. A large part of this waste is not utilized due to the absence of efficient management and collection systems, which is further compounded by a lack of culture in the responsible handling of this material.

Plastic pollution in coastal and marine ecosystems represents a growing threat in Mexico.

According to the Ocean Conservancy [2019], at least 76% of the waste collected during coastal cleanups carried out in the country in 2009 was plastic, equivalent to approximately 8 out of every 10 pieces of waste found on beaches and in marine areas. This reflects the magnitude of the problem and highlights the urgent need to establish effective strategies for the management and reduction of plastic waste in coastal areas.

A representative case of this problem can be seen in the Gulf of California, near the region of Mexicali, Baja California, where Mijares-Mastretta [2012] warns that in order to improve the use of plastic waste, legal actions and active social participation must be implemented, encouraging the recycling of plastic containers, the accumulation of which has had harmful effects on the marine ecosystem.

Among the main consequences, the presence of microplastics in marine sediments has been documented, which poses a direct threat to wildlife. Moore et al. [2001] point out that microplastics are often ingested by marine organisms when mistaken for food, which can lead to intestinal blockages, malnutrition, or death by strangulation, thus critically affecting the region's biodiversity. Given this situation, the Ministry of Social Development [SEDESOL] has proposed comprehensive strategies through its Strategic Plan for Solid Waste Management, aimed at improving waste collection, sorting, and utilization in the country, with special attention to vulnerable coastal and urban areas.

These actions seek to strengthen a sustainable approach to waste management and are an essential component in mitigating the environmental impacts of plastic in Mexico.

Some researchers have tried partially or totally replacing natural aggregates in concrete with plastics such as PET, High-Density Polyethylene [HDPE], Polypropylene [PP], and Polyvinyl Chloride [PVC] [Siddique et al., 2008]. PET in particular has shown promising results when incorporated as a fine or coarse aggregate, depending on its particle size, shape, and percentage of replacement. Research has documented that at moderate levels, PET can maintain and, in some cases, even improve impact energy absorption, abrasion resistance, and thermal insulation [Frigione, 2010; Saikia & De Brito, 2014].

When high percentages are used, losses in compressive strength and internal cohesion can be observed, mainly due to low adhesion between the plastic and the cementitious matrix [Hannawi et al., 2010].

The incorporation of plastic waste such as PET in concrete manufacturing represents a strategy that can bring benefits both in terms of material performance and in reducing the environmental impact associated with construction. Some studies have shown that the controlled inclusion of fine PET can improve its behavior under stress and strain, reduce its density and thermal insulation, which is useful for infrastructure applications [Silva et al., 2022].

The surface texture of crushed PET can positively influence the concrete matrix when combined with modifying additives, helping to improve its integrity, volumetry, and crack resistance [Mannan et al., 2022]. From an environmental perspective, several authors have documented that the use of PET reduces the demand for natural aggregates and minimizes the volume of waste sent to landfills [Batayneh et al., 2007]. On the other hand, there is a lack of consensus regarding the optimal substitution percentage, as in some cases significant losses in concrete strength are reported starting at 5%, while in others specific improvements are observed even with 10% substitution [Choi et al., 2005; Marzouk et al., 2007].

Methodology

This work was developed using a quantitative approach, with a non-experimental design and descriptive statistical analysis of the data collected. The documentary argument is derived from a search of articles in the Scopus and Web of Science databases from the last 10 years, selecting those that address research on concrete that replaces fine aggregate with PET in fractions of 5% and 10% and that report compressive strength results at 28 days.

The mix design proposes the percentages by weight and density of substitution by plastic materials in accordance with the recommendations of the American Concrete Institute [ACI]. It is calculated by applying the direct percentage to the inputs required for the concrete, obtaining the weight of the replacement material in the mix.

Thirteen mixtures that met the above criteria were obtained for analysis, totaling 35 data points, which were compared graphically in reference to the control mixture [the one with 0% replacement]. Evaluated with an analysis in a table containing data extracted from the results reported in the selected articles after reading the full text, a comparative graph was created showing the trends and behaviors of the replacement percentages. Based on the analysis, the replacement percentage with the best performance was identified, with the least variation between the control mixture and the replacement, respectively, to demonstrate that using replacement materials in concrete is efficient and thus promotes recycled concrete in the construction industry and makes the sector more environmentally friendly.

Results

The compressive strength of the thirteen mixtures is presented, coded by article ID in Table 1, comparing the results according to the percentage of fine aggregate replacement by recycled PET of 5% and 10% against 0% replacement, which is the control mixture reported in each article, and serves as a reference for comparing mechanical properties.

Box 1

Table 1

“Percentage of substitution and its mechanical strength results”

ID ARTICLE	% Replacement [Resistance in MPa]		
	0%	5%	10%
15	42.8	-	38
18	22.4	19	-
		16.5	-
22	59.8	60.2	45.8
32	19.3	12.7	9.2
36	31.2	25.9	21.3
37	34.8	-	38
41	26.7	24	18
42	31	-	22.3
43	22.3	19.1	-
47	35	51	38
48	37.8	40	38.3
49	35	46.9	45.36
54	38.7	39.6	38.2

The results presented in Table 1 constitute the starting point for the comparative analysis between the different concrete mixtures with varying substitution percentages.

This table shows the strength values obtained, which allow us to establish a technical reference against which the mechanical performance of the modified mixtures will be evaluated.

The analysis of these control mixtures is essential, as it provides a baseline parameter that allows for objective interpretation of variations in strength based on trends in mechanical behavior, and discusses their possible technical causes.

In order to make an objective comparison of the effect of substitution, we decided to determine the percentage variation of each mixture with 5% and 10% replacement relative to its respective control mixture.

This strategy allowed us to normalize the results between studies with different base strengths, making it possible to make a relative comparison without relying on the absolute strength value of the original concrete.

Equation 1 was applied to obtain the percentage variation based on the following:

$$\text{Variation} [\%] = \left(\frac{f'_{c[PET]} - f'_{c[Control]}}{f'_{c[Control]}} \right) \times 100 [1]$$

Ec.1. Percentage variation in concrete mixes

The percentage variation of the thirteen concrete mixes is presented in Table 2. The data were grouped by substitution percentage, and a descriptive statistical analysis was applied to the percentage variation results.

This includes the calculation of measures of central tendency such as the mean, median, and mode, dispersion, standard deviation, variance, coefficient of variation, and range.

This evaluation made it possible to identify not only the average impact of PET on strength, but also the consistency or dispersion of the results obtained in different studies.

Box 2

Table 2

“Percentage change”

ID ARTiCLE	% change	
	5%	10%
15	-	-11.2%
18	-15.2%	-
	-26.3%	-
22	0.7%	-23.4%
32	-34.2%	-52.3%
36	-17.0%	-31.7%
37	-	9.2%
41	-10.1%	-32.6%
42	-	-28.1%
43	-14.3%	-
47	45.7%	8.6%
48	5.8%	1.3%
49	34.0%	29.6%
54	2.3%	-1.3%

In the case of mixtures with 5% PET substitution, the percentage variation values were analyzed with respect to their respective control mixtures. The analysis yielded an average of -2.60%, suggesting that, on average, this substitution percentage does not generate a significant change in compressive strength compared to mixtures without PET or with 0% replacement. However, the dispersion of the data was considerable, so the standard deviation was calculated using Equation 2:

$$\sigma = \sqrt{\frac{1}{n-1} \sum (x_i - \mu)^2} [2]$$

In this regard, the standard deviation yielded a value of 24.28%, while the variance was 589.74. This value suggests that the behavior of PET at 5% is highly dependent on the mixture design conditions, type of PET, particle size, and other technical factors. In addition, a variation range of 79.9% was obtained, with results ranging from reductions of around -34.2% to increases in strength of around 45.07%, as reported in article ID47.

For the 10% mixture group, applying the same statistical analysis, it was possible to identify that the average percentage variation with respect to their respective control mixtures is -11.99%, indicating that, on average, this substitution ratio caused a more marked reduction in compressive strength compared to the 5% substitution.

While the variance was 572.21, indicating a wide dispersion but slightly less than that observed in the 5% group. The calculated coefficient of variation was 199.49%, which shows highly unstable behavior. The range of variation was 81.9%, ranging from severe losses of up to -52.3% to maximum increases of 29.6%.

The comparative analysis aims to identify a pattern of improvement, decrease, or stability in compressive strength when applying a 5% and 10% substitution.

The substitution percentages and the differences between the compressive strength results are evaluated in each of the articles by means of a technical assessment. These values are compared with the reference mixtures. Standardizing the results under the same percentage facilitates a critical evaluation of the effectiveness of the substitution on the mechanical performance of the concrete.

Box 3

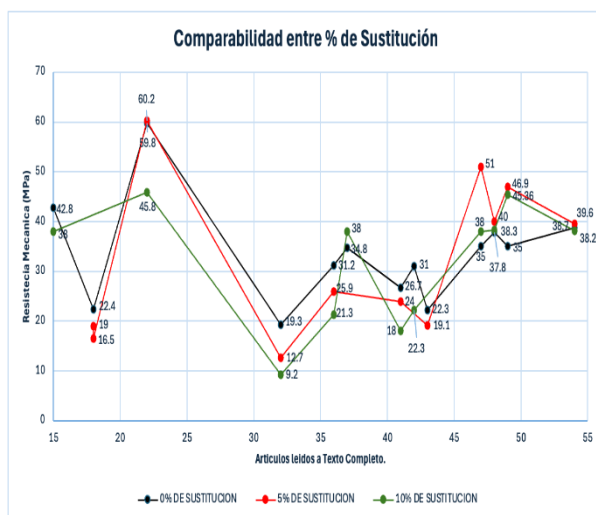


Figure 1

“Compressive strength per item and percentage of substitution”

Source: Own elaboration.

Based on Graph 1, a technical comparative analysis is performed to identify and understand the significant differences between the strength results reported in each of the articles, focusing on highlighting the most relevant variations in relation to the control mix, based on the substitution percentages previously presented and the statistical results obtained.

This influences technical factors such as mix design, cement type, water/cement ratio, curing conditions, or specific characteristics of the plastic material used, and whether they are due to particular experimental design criteria for each study. This critical review provides an answer based on the statistical analyses and the graph presented. Based on the present analysis, the aim is to establish a methodology aimed at optimizing the use of recycled plastics in concrete, which allows the results obtained to be reproduced or improved, guaranteeing both the mechanical performance and the technical and environmental viability of the material developed.

The highest and lowest resistance are identified. We can see that the item with the highest resistance is ID 22, with a resistance of 59.8 MPa for the control mixture, 60.2 MPa for a 5% substitution, and 45.8 MPa for a 10% substitution, respectively.

In this comparative analysis, it can be observed that the highest compressive strength among the selected articles was reported by Espindola-Flores et al. [2024], reaching a value of 60.2 MPa at 28 days. This is attributed to the fact that the 5% percentage allows for homogeneous dispersion of the polymeric material within the cementitious matrix, without significantly interfering with the cement hydration processes. In mixtures with higher substitution percentages, the hydrophobic nature of PET begins to negatively affect the development of the matrix [ibid.], as it reduces the effective contact between water and cementitious compounds, thus limiting the formation of calcium silicate hydrate [C-S-H] gel, which is a fundamental component for concrete strength.

In contrast, with 5% PET, the reaction and hydration of the cement can continue, which favors the formation of a denser, more compact, and more resistant structure. It contributes mechanical properties such as energy absorption, dissipating stress during load testing.

According to the analysis, Article 32 shows the most significant negative results, where flattened and rounded plastic was used as a partial substitute for fine aggregate.

The maximum strength achieved was 12.5 MPa, while the mixture with 5% substitution obtained a strength of 12.72 MPa, exceeding the strength of the control mixture. This article highlights the use of 15% fly ash as a complementary pozzolanic material, identifying that adding this to concrete mixtures results in a minimal decrease in compressive strength compared to those without this material. What we can say is that incorporating supplementary cementitious materials such as fly ash can partially offset the negative effects of PET on cement hydration, thus increasing the strength of the concrete.

In the analyzed article of ID 47, the results show a particular behavior in compressive strength, with a significant increase in strength compared to the control concrete, registering 45.7% higher strength according to the control mixture, replacing 5% and 8.6% for 10%.

This can be explained by the laminar and flattened shape of the PET particles, which, when integrated into the cement matrix, generate a redistribution of stress in the critical areas of failure initiation. Therefore, the plastic particles act as flexible elements capable of absorbing part of the shear stress and transforming it into tensile stress.

This characteristic gives concrete additional deformation capacity before fracture, which does not occur in natural aggregates with spherical morphology and brittle behavior. Furthermore, PET, being non-porous and non-water-absorbent, prevents the formation of micro-hydration zones on its surface, reducing the appearance of weak points due to excess voids at the aggregate/mortar interface, also seen in other articles.

It should be noted that two different gradations of PET particles were used to manufacture the mixtures: the first with sizes between 2 and 4.9 mm and the second, finer, with sizes between 0.05 and 2 mm. They were previously washed using a wet screening method and then dried in the open air under direct exposure to sunlight, thus ensuring the cleanliness and uniformity of the recycled aggregates before their incorporation into the concrete mixture.

Conclusions

The 5% substitution showed an average percentage of -2.60%, indicating a slight reduction on average, while the 10% showed an average of -11.99%, representing a more considerable decrease in resistance. This finding suggests that the higher the percentage of substitution, the greater the negative impact on resistance, a trend also observed in several previous studies.

In terms of consistency between results, the analysis shows that both percentages present high dispersion, although 10% was statistically more stable; the coefficient of variation was 934.02% for 5%, compared to 199.49% for 10%, indicating that the effects of 5% are variable and less predictable between studies.

Although 10% also showed instability, its results are distributed close to its mean, as confirmed by its median of -11.2%, similar to the mean of -11.99%, compared to the more dispersed values in 5% with a mean of -2.6% and a median of -10.1%.

The range of variation was also wide in both cases, indicating that there are extreme cases in which PET substitution has led to severe losses in strength or significant improvements.

These differences are probably due to the diversity of methodologies used in the articles analyzed, such as the type of PET, particle size, mixture design, water-cement ratio, additives, and curing conditions. Statistically, 5% shows a lower average loss of strength, but its high coefficient of variation reveals high instability between studies, which limits its reliability if the mixture variables are not controlled. Ten percent tends to show a clearer reduction in strength, but its results are more statistically consistent.

Therefore, the choice between 5% or 10% as a replacement percentage should depend not only on the strength values obtained, but also on the technical control of the mixture and the acceptable level of risk in the construction project.

Based on a comparative analysis of the reviewed articles, it was found that a 5% PET replacement rate is the most favorable level for the development of plastic-modified concrete.

This allows for homogeneous dispersion of the material within the cement matrix, preventing significant interference with the cement hydration processes and promoting the formation of a more compact and resistant microstructure.

The results obtained also show that finer PET gradation promotes significantly higher compressive strength compared to that obtained in other studies. This behavior can be attributed to the fact that the smaller particles acted as a micro-filler, improving the compaction of the cement matrix by reducing the presence of voids. Their specific surface area also promoted better mechanical anchoring with the cement paste, which increased the concrete's ability to resist compressive loads. This effect contrasts with what was reported in research, where fine PET produced lower strengths. The difference lies in the preparation method applied in that study, in which the washing and gradation control process allows for cleaner, more uniform particles with better particle size distribution.

These conditions ensured that PET did not act solely as an inert substitute but also participated in optimizing compactness and redistributing internal stresses in the mixture.

It was observed that percentages above 10% tend to decrease resistance due to the hydrophobic nature of PET and the progressive loss of cohesion at the paste-aggregate interface, which limits the mixture's ability to form a continuous and dense structure.

The outstanding performance of the 5% substitution suggests that this percentage can be replicated as a viable technical alternative for the industry, ensuring a balance between mechanical performance, plastic waste utilization, and environmental viability, directly contributing to sustainability goals by reducing the extraction of natural aggregates while adding value to a waste material with high environmental impact such as PET, favoring the reduction of pollution and promoting circular economy practices within the construction sector.

To consolidate this proposal as a large-scale solution, future research must focus on optimizing PET preparation and degradation conditions, evaluating compatibility with different types of cement and mineral additives, and exploring the behavior of the material under different environmental exposures.

In this way, progress can be made toward the design of an “optimal” mixture that combines mechanical performance, technical efficiency, and a real contribution to the sustainability of the concrete industry.

Declarations

Conflict of interest

The authors declare that they have no conflicts of interest. They have no competing financial interests or known personal relationships that could have influenced the article presented in this paper.

Authors' contribution

The contribution of each researcher to each of the points developed in this research was defined based on:

Arias Jhovanny: Led the writing of the manuscript, participated in the search and selection of articles, as well as in the extraction of experimental data reported in the literature. He performed the initial processing of the information and collaborated in the structuring of the statistical and technical analyses.

Gutierrez Manuel: Responsible for the comprehensive drafting and cohesion of the article, ensuring clarity and consistency of content. Directly involved in the validation of calculations and statistical review, verifying the accuracy of the results presented.'

Arcos-Vega José Luis: He contributed to the methodological design of the study, defining the criteria for selecting articles and the strategy for comparing mixtures. He also reviewed the entire document, proposing technical and methodological adjustments to strengthen its academic rigor.

Calderón, Julio: He contributed to the writing of specific sections of the manuscript and was responsible for preparing the tables and graphs for the comparative diagrams representing the results. He also participated in the technical review of the visual presentation of the data.

Availability of data and materials

The data supporting the findings of this study are available upon reasonable request from the corresponding author.

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Abbreviations

ACI	American Concrete Institute
ANN	Artificial Neural Network
C-S-H	Calcium Silicate Hydrate
FA	Fly Ash
HDPE	High-Density Polyethylene
MPa	Megapascal
PET	Polyethylene Terephthalate
PP	Polypropylene
PVC	Polyvinyl Chloride
w/c	Water–Cement Ratio
%	Percent
ACI	American Concrete Institute
ANN	Artificial Neural Network
C-S-H	Calcium Silicate Hydrate
FA	Fly Ash
HDPE	High-Density Polyethylene
MPa	Megapascal
PET	Polyethylene Terephthalate
PP	Polypropylene
PVC	Polyvinyl Chloride
w/c	Water–Cement Ratio
%	Percent

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