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Predicting the Mechanical Thresholds of Recycled HDPE-Modified Concrete Using a Novel Non-Destructive Structural Quality Index

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ABSTRACT

This study examines the mechanical and physical properties of sustainable concrete containing recycled high-density polyethylene (HDPE) waste. Coarse aggregate was replaced with crushed HDPE granules at 0%, 10%, 20%, and 30%, with a constant 1% proportion of hand-produced HDPE fibers remaining in all modified mixtures. The apparent density, compressive strength, flexural strength, and ultrasonic pulse velocity (V) of the composite matrix were measured after 28 days of in vitro testing. The experimental results demonstrated a proportional drop in density, mechanical strength, and sound velocity as polymer content increased, which was attributed to microstructure discontinuity and interfacial transition zone weakness. Unlike common percentage-based evaluations of decrease, this research proposes a new approach based on physical attributes and linear regression modelling. The non-destructive structural quality index (SQI) reliably forecasts mechanical stress thresholds based on density and sound wave velocity measurements, with an error margin of no more than ±6% and a coefficient of determination (R^2), ranging between 0.82 and 0.97. The findings demonstrate that the created mathematical models provide a highly reliable non-destructive quality assessment tool for optimizing the application of environmentally friendly, lightweight, low-strength concrete in a circular economy framework.

التنبؤ بالحدود الميكانيكية للخرسانة المعدلة بـ HDPE المعاد تدويره باستخدام مؤشر جودة إنشائي مبتكر وغير إتلافي

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الكلمات المفتاحية:
البولي إيثيلين عالي الكثافة المعاد تدويره
سرعة الموجات فوق الصوتية
مؤشر جودة الهيكل
النمذجة التنبؤية
الخرسانة خفيفة الوزن الصديقة للبيئة.

الملخص

تتناول هذه الدراسة الخصائص الميكانيكية والفيزيائية للخرسانة المستدامة المحتوية على نفايات البولي إيثيلين عالي الكثافة (HDPE) المعاد تدويرها. تم استبدال الركام الخشن بحبيبات البولي إيثيلين عالي الكثافة المطحونة بنسب 0%، 10%، 20%، و30%، مع الإبقاء على نسبة ثابتة قدرها 1% من ألياف البولي إيثيلين عالي الكثافة المنتجة يدويًا في جميع الخلطات المعدلة. تم قياس الكثافة الظاهرية، ومقاومة الضغط، ومقاومة الانحناء، وسرعة النبضات فوق الصوتية (V) للمصفوفة المركبة بعد 28 يومًا من الاختبارات المعملية. أظهرت النتائج التجريبية انخفاضًا متناسبًا في الكثافة، والمقاومة الميكانيكية، وسرعة الموجات فوق الصوت مع زيادة محتوى البوليمر، وهو ما يُعزى إلى عدم تجانس البنية المجهرية وضعف منطقة الانتقال البينية. وخلافًا للتقييمات الشائعة القائمة على النسب المئوية للانخفاض، يقترح هذا البحث منهجًا جديدًا يعتمد على الخصائص الفيزيائية ونمذجة الانحدار الخطي. يتنبأ مؤشر جودة الهيكل غير المتلف (SQI) بدقة بعتبات الإجهاد الميكانيكي بناءً على قياسات الكثافة وسرعة الموجات الصوتية، بهامش خطأ لا يتجاوز ±6%، بمعامل تحديد (R^2) يتراوح بين 0.82 و0.97. وتُظهر النتائج أن النماذج الرياضية المُنشأة تُوفر أداة تقييم جودة غير متلفة عالية الموثوقية لتحسين استخدام الخرسانة الصديقة للبيئة، خفيفة الوزن، ومنخفضة المقاومة في إطار الاقتصاد الدائري.

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Introduction

It consists mainly of cement, water, and aggregates of both fine and coarse types. The properties of concrete can be controlled by adjusting the proportions of its components or adding improved materials to develop its performance and meet modern construction requirements. In contrast, Plastic waste is one of the most widespread materials globally widespread, resulting in the accumulation of huge quantities of them Annually. For example, total polyethylene waste amounted to approximately 220 million tons in 2024, an increase of nearly 10% compared to 2021, and this figure is expected to increase continuously. These wastes cause significant environmental challenges such as visual pollution and serious environmental damage, making recycling and using them in new sectors an urgent priority [1].

High density polyethylene (HDPE) is a widely used thermo-polymer in engineering applications, thanks to its outstanding physical and mechanical properties, such as its high resistance to shock, lightweight, and good resistance to moisture and chemicals. In recent years, there has been an increase in interest in recycling plastics and using them as additives in concrete [2] [3] [4]. To improve mechanical performance and reduce environmental impact, HDPE is among the most prominent of these materials [5].

Adding HDPE to concrete in the form of granules or fibers is one of the most promising methods for improving certain mechanical properties, such as impact and flexural strength. The physical form of the admixture, whether granules or fibers, and the proportions in which it is added can significantly affect the performance of the final material [6] [7]. Polyethylene has been used as an aggregate in concrete in various forms and methods, and numerous tests have been conducted to determine its effect on concrete properties. In many cases, this has resulted in a decrease in some mechanical properties, such as compressive strength, and a significant improvement in impact absorption. For example, when polyethylene is added as a coarse aggregate, the compressive strength of concrete decreases at high replacement ratios [8]. When used as fibers within certain limits, it improves compression and flexural strength [9] [10] [11].

This study aims to evaluate the effect of adding high-density polyethylene (HDPE) in different proportions and physical forms (granules and fibers) on the mechanical and physical properties of concrete, such as compressive strength and density. The study also seeks to determine the optimal proportion and examine the results of different properties and their interrelationships. This research paves the way for broader applications in civil engineering, polymers, and construction.

Used Materials and Mixing Ratios

Ordinary Portland cement was used, CEM I 42,5R. The water used in mixing is drinking water, which is free of organic matter. The aggregate used was a combination of two fine aggregate types: the first was soft (sand), which was sourced locally from Misurata. Its absorption ratio was 0.355%. The second is Italian gravelly marble aggregate, which has an absorption rate of 2.02% and a specific weight of 2.63. Both of which fall within the limits of the granular gradient curve found in Libyan Specifications for fine aggregates (LNCSM49-2002) [12]. Forty percent gravel and sixty percent sand were the mixing rates for the two aggregate types. The polyethylene used was obtained from collection and recycling facilities. Part of it was ground into small particles the size of typical aggregates, then sorted by size and sieved. The remainder was manually cut lengthwise into fibers. These fibers measured 38–42 mm in length, 2–3.5 mm in width, and 1.8 mm in thickness. Fig. 1 shows the polyethylene fibers and granules. The study was based on a real-world program that comprised four concrete mixtures with varying amounts of polyethylene residues.



Fig. 1 Polyethylene granules and fibers used in mixtures

Different proportions of the aggregate were replaced with polyethylene aggregate based on its particle size distribution, and the mixing ratios were determined using the volumetric formula for the mix design. The mixes were designated as follows: R0 is the reference mix, which is free of polyethylene. The other mixes contain proportions of HDPE as a substitute for natural aggregate, with CP10 containing 10% polyethylene aggregate, CP20 containing 20%, and CP30 containing 30%. The last three mixes also contain 1% polyethylene fibers as an additive. The mixing ratios for each of the mixes are shown in Table 1. The materials underwent various mechanical and physical tests.

Material Processing and Mixing

A total of 24 concrete cubes with dimensions of 100 mm, six for each mixture, were prepared to test the compression strength at 7 and 28 days, as well as to measure the density and the ultrasonic pulse velocity. Prisms with dimensions of 100 x 100 x 500 mm were also prepared for the flexural test, three samples for each mix.

Table 1: Ingredient ratios for each mixture

Mix	Quantity (Kg/m^3)				
	Cement	Water	Sand & gravel	HDPE aggregate	HDPE Fiber
R0	350	183.7	1200.0	0.0	0.0
CP10	350	169.2	1079.2	31.7	28.3
CP20	350	168.6	960.0	57.3	28.3
CP30	350	167.7	840.0	85.9	28.3

The dry ingredients were thoroughly mixed using a mechanical mixer, then water was added, and mixing continued until the desired consistency was achieved.

The concrete was poured directly into molds and compacted using a mechanical vibrator after mixing and conducting a slump test on the fresh concrete. The molds were kept at laboratory temperature (23 ± 2°C) for a full day without any external influences. After 24 hours, the molds were removed, and the samples were numbered. The samples were then immersed in water until the test date. After 7 days of immersion, three cubes of each mixture were removed, and their surfaces were dried for compressive strength testing. After 28 days, the same process was repeated for compressive strength testing, but this time the density was measured, and an ultrasonic test was performed on the cubes. On the same day, the prisms were removed, and a flexural test was conducted.

Results

A slump test was performed on all mixtures immediately after mixing. The water content was adjusted to achieve the same slump (70 mm) for all mixtures. This step involves comparing the strength of the mixtures while controlling for the reduced resistance factor resulting from an increased water content.

Based on weight and volume, the drying density of concrete cubes was firstly calculated at 28 days. Ultrasonic pulse velocity (UPV) testing was also performed on the same samples before the compressive strength test. A PUNDIT Ultrasonic Pulse Velocity Tester instrument was used with a time resolution of 0.1 used. For the compressive test, an AUTOTEST device was used. Table 2 shows the results of the hardened concrete tests. The density of hardened concrete is a fundamental property as it reflects the material's cohesion and strength after the hardening process is complete. The results in the table show a decrease in density with increasing proportions of HDPE in the mix,

a natural consequence of its lighter weight compared to natural aggregates. This aligns with previous studies showing a direct relationship between density and the compressive and flexural strength of concrete; the higher the density, the greater the concrete's strength [13], a pattern observed when HDPE is substituted in concrete [8].

The UPV test relies on the speed at which sound waves travel through the concrete. The test was performed after determining the density of the cubic samples. According to classifications from several reference works, the UPV data presented in Table 2 indicate that the concrete is in an ideal condition for all mixes, although this decreases with increasing polyethylene substitution ratios.

Table 2: Mixture types and substance proportions for each mixture

Mix	Density (kg/m³)	UPV km/s	Compressive Strength (MPa)		Flexural Strength (MPa)
			7d	28d	
R0	2309	4.38	27.97	33.14	3.92
CP10	2116	3.97	17.37	25.20	3.49
CP20	2076	3.93	17.01	22.18	3.45
CP30	1984	3.86	16.11	20.47	3.09

The compressive strength test of hardened concrete cubes was conducted on the mixes on the seventh and twenty-eighth days. The test results showed a decrease in strength with increasing polyethylene substitution, both at the early stage (day 7) and after 28 days. The compressive strength decreased by 38%, 39%, and 42% compared to the reference mix R0 on the seventh day for mixes CP10, CP20, and CP30, respectively. For the same mixes, the compressive strength decreased by 24%, 33%, and 38% on the twenty-eighth day, respectively. Unlike natural aggregates, HDPE has a smooth, non-polar surface that minimizes mechanical interference and reduces chemical adhesion. Furthermore, the lower modulus of elasticity of HDPE compared to mineral aggregates creates localized deformation zones and stress concentrations under compressive loads, accelerating crack initiation and propagation.

This decrease is consistent with previous findings by researchers who replaced aggregates in concrete with HDPE granules or other types of plastics. This is attributed to the fact that polyethylene, with its weaker mechanical properties compared to conventional aggregates [11] and its inability to form a strong chemical bond with cement paste, exhibits a weak interfacial transition zone (ITZ) between the hydrophobic HDPE particles and the surrounding cement paste. This directly and negatively impacts the compressive strength of the concrete. Also, the reduced compressive strength, unlike that of natural aggregates, can be explained by the fact that HDPE has a smooth, non-polar surface that minimizes mechanical interference and chemical adhesion. Furthermore, the lower modulus of elasticity of HDPE compared to mineral aggregates creates localized deformation zones and stress concentrations under compressive loads, which may accelerate crack initiation.

All prisms were tested for flexural strength 28 days after casting. Despite the addition of polyethylene fibers to enhance flexural strength, a decrease in strength was observed as the proportion of HDPE in the mixture increased. Simultaneously, the sample's collapse pattern at test time, as shown in Figure 2, indicates that the crack width decreased with increasing HDPE content, unlike the control sample, which completely detached upon collapse. The narrowing of cracks with increasing HDPE content is attributed to a change in failure mode from brittle fracture (in the control mixture) to ductile or semi-ductile behavior, where crack propagation becomes slower and more energy-intensive.

Analysis

According to earlier findings on concrete's density, wave transfer velocity, compressive strength, and flexural strength indicated in Table 3 and Fig. 3, a decrease is seen as the percentage of polyethylene substitution in the mixture increases.



Fig. 2: failure pattern in flexural test

Table 3: Percentage of reduction in properties compared to the reference mixture

Concrete Mix	Compressive Strength-28d	Flexural Stress (MPa)	Ultrasonic	Density
R0	0%			
CP10	24%	11%	9%	8%
CP20	33%	12%	10%	10%
CP30	38%	21%	12%	14%

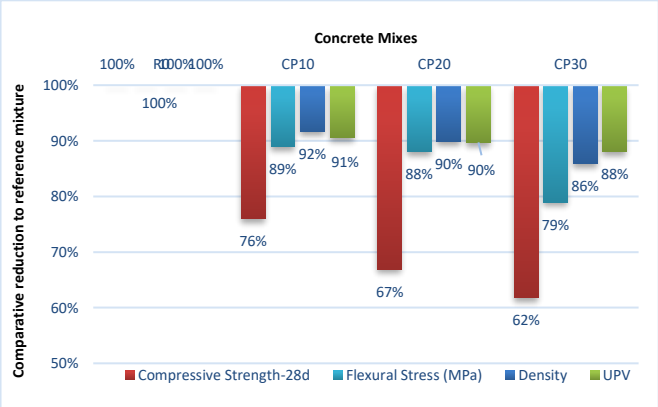


Fig. 3: Relative Value for decrease in the property compared to reference mix

The reduction in properties contributes to establishing a common relationship between these attributes. This graph also includes a study of the percentage decrease in the quality of the concrete mix compared to the reference mix R0. The relationships for the percentage decrease in the studied properties can be plotted as shown in Fig. 4, which illustrates the linear relationship for each property. These relationships can be summarized as follows: as the percentage of HDPE added to the concrete mix increases from 10% to 30%, the percentage decrease in mechanical properties increases compared to the reference mix, particularly in compressive and flexural strength.

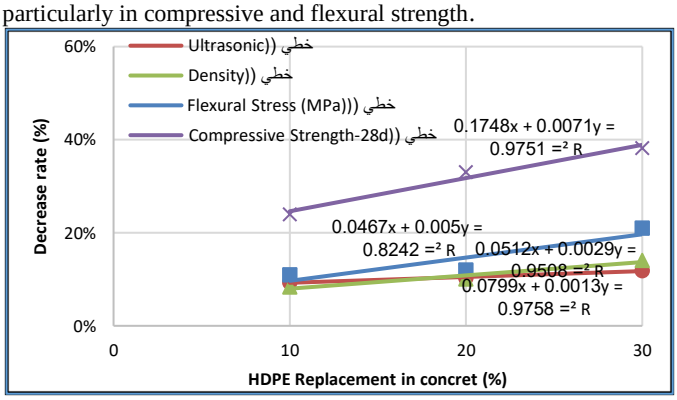


Fig. 4: Relationship between the replacement ratio of HDPE for concrete and the decrease in various properties

Model Development and Validation

1. Experimental Regression Models

To establish a reliable predictive framework for the mechanical performance of HDPE modified concrete, empirical modeling was employed. Unlike traditional methods that relate mechanical strength solely to volumetric replacement ratios, this study presents an approach based on physical properties. Linear regression analysis was performed to determine direct correlations between 28-day compressive strength (fc,28) as the dependent variable, and hardened density (ρ) and ultrasonic pulse velocity (V) as independent physical predictive variables.

Based on the experimental datasets, the empirical relationship calibrating compressive strength against the concrete hardened density is expressed as follows:

Based on the experimental data sets in Table 2, the empirical relationship that calibrates compressive strength versus density of hardened concrete is expressed as in Equation 1:

$$f_{c,28}(\rho) = 0.0385\rho - 56.45 \quad (1)$$

Here, $f_{c,28}$ represents the expected compressive strength (MPa) and ρ the density after hardening (kg/m³). This positive linear correlation confirms the direct effect of increasing the density of the base material on structural strength, as the decrease in apparent density resulting from the addition of lightweight, HDPE aggregate leads to a mathematically proportional decrease in compressive strength.

Simultaneously, a predictive model for non-destructive testing (NDT) was developed by relating the compressive strength to the UPV values. The resulting mathematical expression is defined as in Equation 2:

$$f_{c,28}(V) = 24.32V - 72.84 \quad (2)$$

Where V represents the ultrasonic pulse velocity (km/s). This formula utilizes the wave propagation velocity as an indicator of the homogeneity of the internal microstructure and porosity, providing a non-destructive approach to estimating mechanical thresholds.

2. Structural Quality Index (SQI) Formulation

To standardize the evaluation of composite concrete mixes containing varying proportions of recycled polymers, a new Structural Quality Index (SQI) is proposed. This index serves as a benchmark performance measure relative to a control matrix (R0), assessing relative structural integrity through physical and non-destructive indices.

Assuming the experimental compressive strength of the reference mix after 28 days (33.14 MPa) as the baseline (100%), the SQI can be calculated using density measurements or ultrasonic velocity measurements, as described in Equations (3) and (4), respectively.

$$SQI_\rho = \left(\frac{0.0385\rho - 56.45}{33.14}\right) \times 100\% \quad (3)$$

$$SQI_V = \left(\frac{24.32V - 72.84}{33.14}\right) \times 100\% \quad (4)$$

The application of the SQI model provides a practical advantage for industrial applications, allowing ready-mix concrete plants and quality control engineers to verify the structural grade of eco-friendly lightweight concrete blocks or slabs through on-site NDT methods without resorting to destructive crushing tests.

3. Validation and Reliability Analysis

The reliability and predictive accuracy of the proposed linear regression models were validated by back counting the compressive strength profiles of the experimental concrete designations (R0, CP10, CP20, and CP30) and comparing them against the actual laboratory destructive testing measurements.

The reliability and accuracy of the prediction of the proposed linear regression models were verified by back-calculating the compressive strength profiles of the experimental concrete labels (R0, CP10, CP20, and CP30) and comparing them with actual laboratory destructive test measurements as in Table 4. This table summarizes the comparative validation matrix, outlining the experimental values, model predictions, absolute errors, and percentage accuracy.

Table 4: Validation matrix and error analysis of the predictive models.

Mix ID	Actual $f_{c,28}$ (MPa)	Predicted $f_{c,28}(\rho)$ (MPa)	Error (%)	Predicted $f_{c,28}(V)$ (MPa)	Error (%)
R0	33.14	32.44	-2.11%	33.68	+1.63%
CP10	25.20	25.02	-0.71%	23.71	-5.91%
CP20	22.18	23.48	+5.86%	22.74	+2.52%
CP30	20.47	19.93	-2.64%	21.03	+2.74%

As the error analysis showed, the density-based model (SQI_ρ) demonstrated exceptional predictive accuracy, with a maximum deviation of +5.86% in the CP20 mix and a minimum error of -0.71% in the CP10 mix. Similarly, the non-destructive testing model based on ultrasonic velocity (SQI_V) demonstrated high reliability, keeping all absolute error margins within the acceptable limit for structural engineering of ±6%.

The values of equations 1 and 2 can be represented graphically (Fig. 5) by substituting the results obtained from ρ and V for the different mixtures.

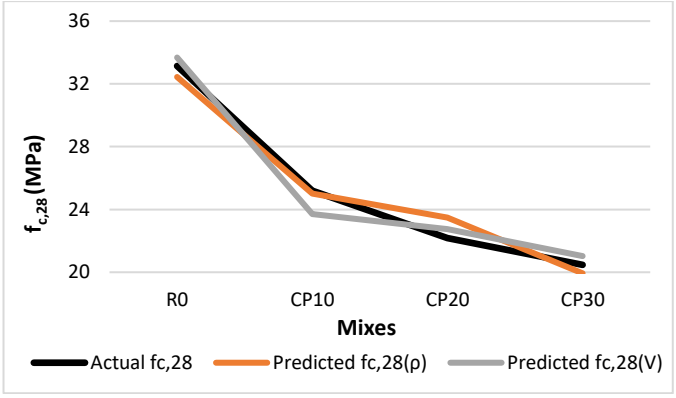


Fig. 5: The relationship between the actual compressive strength and the innovative model as a function of wave velocity and density

The close convergence between the experimental results and the experimental paths confirms the mathematical soundness of the equations, thus confirming their readiness to characterize low-strength, sustainable plastic concrete within the volumetric limits examined (from 0% to 30%).

4. Correlation Between Hardened Density and UPV

A direct proportional correlation was established between the hardened density (ρ) and the ultrasonic pulse velocity (V) of the concrete composites. Theoretically, both parameters serve as global indicators of the internal microstructure, soundness, and compactness of the concrete matrix.

As illustrated by the experimental data, a reduction in concrete density—triggered by the volumetric substitution of dense mineral aggregates with lightweight recycled HDPE granules—simultaneously yielded lower UPV values. This co-dependent decline is attributed to the fact that acoustic waves travel faster in denser, highly continuous solid media. The introduction of hydrophobic polymer particles diminishes bulk density and promotes microscopic discontinuities and a weaker interfacial transition zone (ITZ), which scatter the ultrasonic stress waves and prolong their transit time.

A direct correlation has been established between the solidified density (ρ) and the ultrasonic pulse velocity (V) of the composite concrete. Theoretically, both parameters are comprehensive indicators of the internal microstructure, durability, and cohesion of the concrete matrix.

As experimental data demonstrate, the reduction in concrete density resulting from the volumetric replacement of dense mineral aggregates with lightweight recycled HDPE granules simultaneously led to a decrease in ultrasonic pulse velocity. This correlational decrease is attributed to the fact that sound waves travel faster in denser, more homogeneous solid media. The introduction of hydrophobic polymer particles reduces the overall density, enhances micro-homogeneity, and weakens the interfacial transition zone (ITZ), thus scattering the ultrasonic stress waves and prolonging their transmission time.

By optimizing the linear regression, the reciprocal mathematical relationship that calibrates the UPV against the hardened density is formulated as in Equation 5:

$$V(\rho) = 0.0016\rho + 0.648 \quad (5)$$

Where V is the predicted UPV (km/s), and ρ is the apparent density after hardening (kg/m³). The high accuracy of this experimental model in predicting the limits of both the reference mix (R0) and the highly modified plastic composite (CP30) confirms that non-destructive acoustic evaluations can accurately reflect physical density changes in sustainable and environmentally friendly concrete applications.

Limitation of the study

The results of this study are subject to the following limitations:

Local Materials: The natural aggregates used (sand from Misrata and marble gravel from Italy) have specific particle sizes and absorption characteristics. Results may vary depending on the aggregate source.

HDPE shape and size: HDPE granules were crushed to match the fine aggregate gradation, and the fibers were manually cut to approximate dimensions (38–42 mm in length). Different particle geometries or fiber size ratios may affect the mechanical behavior.

Curvature Time: Mechanical properties were evaluated only at 28 days. Long-term performance (e.g., 56 and 90 days) and durability aspects (freeze-thaw, sulfate attack, and creep) were not studied.

Constant Workability Approach: The water content was adjusted to achieve a constant slump of 70 mm, resulting in slight variations in the water-to-cement ratio. This may have partially contributed to the observed strength reductions.

Limited Substitution Ratios: Only volumetric substitution rates of 0%, 10%, 20%, and 30% were tested. Extrapolation beyond this range using the proposed linear models is not recommended.

Fiber Presence: All blends containing HDPE contained 1% fiber by volume of the aggregate, while the control blend (R0) contained no fiber. Therefore, the combined effect of granules and fibers was evaluated, not granules alone.

Future studies should address these limitations by testing a wider range of HDPE ratios, independently varying fiber content, and investigating long-term durability.

Conclusion

Previous laboratory results show that replacing aggregates in concrete with HDPE reduces strength and density properties. This reduction manifests as a decrease in the concrete's compressive and flexural strength, with the decrease increasing as the HDPE content increases. Furthermore, using HDPE results in lighter (lower-density) concrete, which alters its physical properties, impacting stiffness and homogeneity, as evidenced by the lower UPV values. There is a clear trade-off between properties, for example, between reducing concrete density (and thus producing lighter concrete) and preserving its mechanical properties (especially compressive strength). There is a clear balance between properties, for example, between reducing concrete density (and thus producing lighter concrete) and preserving its mechanical properties (especially compressive strength). The developed performance index can be used in similar cases to determine the percentage loss of properties in different applications. This requires modifying, studying, and comparing various data points, such as aggregate type and replacement ratios, with this index.

If the primary goal of the application is to produce lightweight concrete with potential thermal insulation properties, the use of polyethylene may be feasible. However, the significant reduction in compressive strength must be considered, limiting its use in structures requiring high strength.

Overall, these results indicate that replacing aggregates with polyethylene, even in low proportions, negatively impacts the mechanical properties of concrete but achieves the goal of reducing density. The acceptability of such concrete depends on the specific application and engineering requirements of the project.

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