

DOI: 10.34031/2071-7318-2026-11-3-21-31

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## MECHANICAL AND MICROSTRUCTURAL BEHAVIOR OF CONCRETE WITH LDPE WASTE AS PARTIAL FINE AGGREGATE REPLACEMENT

**Abstract.** Waste plastic disposal poses a significant global environmental challenge due to its health risks, high disposal costs, and the difficulty of landfill management. Unauthorized dumping exacerbates the problem, highlighting the need for sustainable reuse solutions. Hence, there is a crucial need to explore alternative methods for reusing plastic waste for other purposes, and concrete has been determined as one of the viable options to use the plastic waste as a part of concrete's aggregate. Therefore, this study aims to illustrate the use of Low-Density Polyethylene (LDPE) in Jordan as a partial replacement for fine aggregate in 40 MPa concrete and evaluating its impact on the mechanical and physical properties of concrete based on the 0 %, 5 %, 10 %, 15 %, and 20% percentage of plastic replaced. By preparing and testing the five different concrete mixes with LDPE replacement at a 0.4 water-cement ratio (W/C). The inclusion of plastic aggregates resulted in a consistent reduction in mechanical properties with increasing plastic aggregate replacement, where compressive strength declined from 42.5 MPa (0 %) to 25.4 MPa (20 %), split tensile strength from 3.8 MPa to 2.3 MPa, and flexural strength from 5.2 MPa to 3.2 MPa, showing 40.2 %, 39.5 %, and 38.5 % respectively maximum reductions. Therefore, plastic can be considered an environmentally friendly material when used as a partial replacement for fine aggregates in concrete, depending on its strength properties. Its suitability differs for structural, light structural, and non-structural applications in constructions.

**Keywords:** mechanical properties of concrete, polyethylene (LDPE) additives, partial replacement for fine aggregate, microstructural behavior of concrete, plastic waste.

**Introduction.** Plastic waste has become one of the most pressing environmental challenges of the 21st century. Though durable and versatile, improper disposal and slow degradation cause severe pollution and ecological harm when they are not handled properly. In 2019, the world made 368 million metric tons of plastic, yet recycling rates are still low after decades of work. Some plastics, such as PET, PVC, and polyethylene, can be recycled in different ways. Some need mechanical recycling, while others need more complex chemical or enzymatic techniques. New methods including pyrolysis, gasification, and hydrothermal liquefaction show promise for recycling plastics that are challenging to recycle. Also, biocatalytic methods like enzyme-based degradation are good for the environment. To move from landfilling to sustainable recycling and foster a circular economy for plastics, governments, businesses, and the public must all work together [1].

Plastic garbage is a common threat to health and the environment, and it may be found in both cities and rural regions. Managing plastic waste demands both traditional methods and innovative solutions to tackle environmental and economic challenges. Traditional waste management methods—including gasification, pyrolysis, and incineration—enable energy recovery but face limitations such as hazardous emissions and toxic byproducts. Landfilling and mechanical recycling remain practical options, yet they contribute to environmental pollution or demand exten-

sive sorting efforts. Meanwhile, emerging technologies like microwave-assisted conversion and plasma treatment offer energy-efficient alternatives, though scalability and cost-effectiveness remain key challenges. Biochemical techniques and polymer redesign give eco-friendly possibilities, however with limitations in production and pricing. A balanced strategy combining these solutions is necessary for sustainable plastic waste management [2].

The scientific community is becoming more engaged in tackling these important challenges as a result of growing knowledge of the detrimental effects plastic waste has on the environment and society [3]. In order to transform plastic trash into useful feedstocks for the production of new products, innovative technological solutions are being developed, including chemical recycling and pyrolysis techniques [4, 5]. Plastic waste management needs good identification and processing of varied plastic materials, each with distinct qualities and recycling issues. The most popular plastics include Polyethylene Terephthalate (PETE), High-Density Polyethylene (HDPE), Polyvinyl Chloride (PVC), Low-Density Polyethylene (LDPE), Polypropylene (PP), and Polystyrene (PS), along with various specialized versions. International standards control their classification and recycling operations. While some plastics like PETE and HDPE are commonly recycled, others such as PVC and mixed plastics offer technological and economic challenges. Emerging technologies and standardized approaches are critical to improving plastic waste

valorization across all categories, supporting a circular economy while minimizing environmental impact [6].

Hameed and Ahmed [7], studied the potential of utilizing plastic waste, particularly Polyethylene Terephthalate (PET), as a sustainable additive in cementitious materials. The results demonstrate that introducing PET into cement mortar not only reduces the density of ordinary concrete but also enhances its mechanical qualities at optimal concentrations. Specifically, a 1wt. % PET content yields peak compressive and splitting tensile strengths, while a 7wt. % PET mixture improves flexural strength by up to 37.93 %. This strategy delivers a combined environmental and economic benefit by converting plastic waste into value-added construction materials with higher performance qualities. The findings indicate PET-modified mortar as a possible solution for eco-friendly building practices.

Another study [8] investigated the effects of incorporating polyethylene terephthalate (PET) strap waste fibers into concrete, evaluating their impact on both fresh and hardened concrete properties. The fibers, produced by simple cutting of PET straps, were added in volumetric fractions ranging from 0 % to 0.5 %, with aspect ratios of 2.5 and 3. Vivek's [9] research found that replacing 5–20 % fine aggregate with LDPE in 20 MPa concrete reduced compressive strength by 35–50 % but improved tensile through fiber reinforcement. The materials show promise for non-structural applications while recycling plastic waste.

According to the study [10], the most effective plastic aggregates used in concrete mixtures should be irregular in shape, have a rough surface texture, and be sufficiently fine to prevent creating critical failure planes. Additionally, they should be well-graded to roughly match the sand they replace. The findings indicate that with an appropriate mix design,

reductions in strength can be minimized to acceptable levels, [10, 11] reported that the inclusion of plastic materials into concrete mixtures reduce their compressive strength but enhance its ability against impact conditions.

This research analyzes the potential of using low-density polyethylene (LDPE) as a sustainable partial replacement for fine aggregate in 40 MPa concrete, addressing both construction material demands and environmental concerns. The study focuses on incorporating LDPE with quartz sand and quartz stone, materials selected for their local abundance in Jordan, where limited research exists on their combined applications in concrete mixtures. While the experimental work was conducted in Russia, the findings are particularly relevant for Jordan, where quartz-based materials are widely available but underutilized in sustainable concrete production. The use of these readily available materials could contribute to waste reduction and promote environmentally friendly practices in Jordan's industrial sectors.

#### Materials and Methodology.

**Materials.** The materials used in this experimental study were carefully selected to ensure consistency and reliability in the results. The key components include:

**Cement.** Ordinary Portland Cement (OPC) M500 (Russia), was used as the primary binding material. Cement provides the necessary adhesive properties to bind all the constituents of concrete together.

**Fine Aggregates.** Fractionated quartz sand passing through a 4.75 mm sieve, was used as fine aggregate. The peculiarity of the offered quartz is the presence of coarse-grained sands, with a large fineness modulus up to M 3.5 [13]. Quartz sand has a rounded shape of the part with a low content of clay inclusions and inclusions of soft rocks. The resulting quartz sand undergoes additional enrichment and drying. The moisture content is up to 0.2 % Table 1.

Table 1

Comparing of Chemical Properties of Quartz sand

Chemical Properties of Quartz sand		
Major Oxides	In Jordan (Ras En Naqb) Ministry of Energy and Mineral Resources [12]	In Russia (Crystal Mountain-гора хрустальная) [13]
SiO <sub>2</sub>	98.7	98.9
Al <sub>2</sub> O <sub>3</sub>	0.52	0.62
Fe <sub>2</sub> O <sub>3</sub>	0.04	0.07
Na <sub>2</sub> O+K <sub>2</sub> O	0.11	0.105

**Coarse Aggregates.** Crushed stone aggregates (vein quartz) with a maximum nominal size of 20 mm were used. Crushed vein quartz is sharp-edged, rough-surfaced, and flat edges with an uneven – unlike rounded river or quarry sands. Its grains are

chemically clean, has a minimal clay content and is completely free of organic inclusions.

**Low-Density Polyethylene (LDPE) Plastic Granules.** LDPE plastic waste was processed into granules of a specific size range (4–5 mm) as shown in the (Fig. 1) to ensure uniform distribution within

the concrete mix. The plastic granules were used as a partial replacement for aggregates at varying percentages (e.g., 5 %, 10 %, 15 %, and 20 %).



Fig. 1. shows the granules of a specific size range (4–5 mm) of LDPE

**Water.** Potable water, free from harmful chemicals and impurities, was used for mixing and curing the concrete samples. The water-cement ratio ( $w/c=0.4$ ) was maintained as per mix design requirements to achieve the desired workability and strength ASTM C187.

**Replace material proportion.** The experimental study focused on evaluating the behavior of

40 MPa concrete, ( $w/c$  0.4) with LDPE plastic waste replacing 5 %, 10 %, 15 %, and 20 % of fine aggregate by weight, comparing it to a control mix (0% plastic). The design characteristic strength was set at 40 MPa as shown in the Table 2, with tests conducted on compressive, tensile, and flexural strength, workability and density to determine optimal replacement levels.

Table 2

Comprehensive Concrete Design Mix

MIX	MIX A (control)	MIX B 5 %	MIX C 10 %	MIX D 15 %	MIX E 20 %
Materials	mass per 1 m <sup>3</sup>				
Portland cement	390	390	390	390	390
LDPE	0	36.6	73.2	109.8	146.4
Construction sand	732	695.4	658.8	622.2	585.6
Coarse aggregate	1139	1139	1139	1139	1139
Water	175.5	175.5	175.5	175.5	175.5

**Mixing and casting.** For the mixing the materials, we used concrete mixer apparatus (drum type with motor, inlet, and discharge chute) (Fig. 2). The compressive strength was tested on 100×100×100 mm concrete cubes according to BS EN 12390-3 (fresh in molds and cured), while the split tensile strength was evaluated on cylindrical specimens (150 mm diameter × 300 mm height) following ASTM C496/C496M and the flexural strength was evaluated on prismatic specimens 100×100×500 mm according to ASTM C78/C78M. The experimental procedure involved uniformly blending cement, sand, coarse aggregates, and LDPE plastic granules

at replacing of 0 %, 5 %, 10 %, 15 %, and 20 % of fine aggregate with a controlled water-cement ratio of 0.4. The fresh concrete was systematically placed into steel molds (Fig. 3) – pre-treated with a releasing agent – in three layers, each compacted to ensure proper consolidation. For concrete workability, conducted slump test. After demolding at 24 hours, specimens were water-cured for 28 days. Post-curing, compressive strength, flexural strength, splitting tensile, and Ultrasonic Pulse velocity (UPV) tests were conducted. The testing apparatuses are showing in (Fig. 4, 5).



Fig. 2. Shows mixer apparatus.



Fig. 3. Shows molds with treating.



Fig. 4. Shows testing machine C040PN

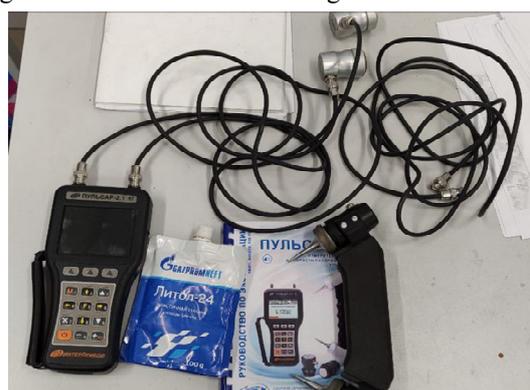


Fig. 5. Shows Ultrasonic device ПУЛЬСАР-2.1.

**Abbreviations and definitions**

ASTM C187: American Society for Testing and Materials (Standard Test Method for Amount of Water Required for Normal Consistency of Hydraulic Cement Paste).

BS EN 12390-3: British Standard that specifies the testing of concrete cubes to assess their compressive strength accurately.

ASTM C496/C496M: American Society for Testing and Materials (Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens).

ASTM C78/C78M: American Society for Testing and Materials (Standard Test Method for Flexural Strength of Concrete).

ASTM C138/C138M-14: American Society for Testing and Material.

**Results and discussion**

**Compressive strength.** The study evaluated the compressive strength of concrete with 0-20% plastic aggregate replacement over 28 days, revealing two key findings: while all specimens gained strength with age, plastic-modified concrete consistently underperformed compared to conventional mixes, showing lower compressive strength 38.6, 34.2, 29.8, 25.4 MPa depending on replacement percentage 5, 10, 15, 20 % respectively as shown in the (Fig. 6).

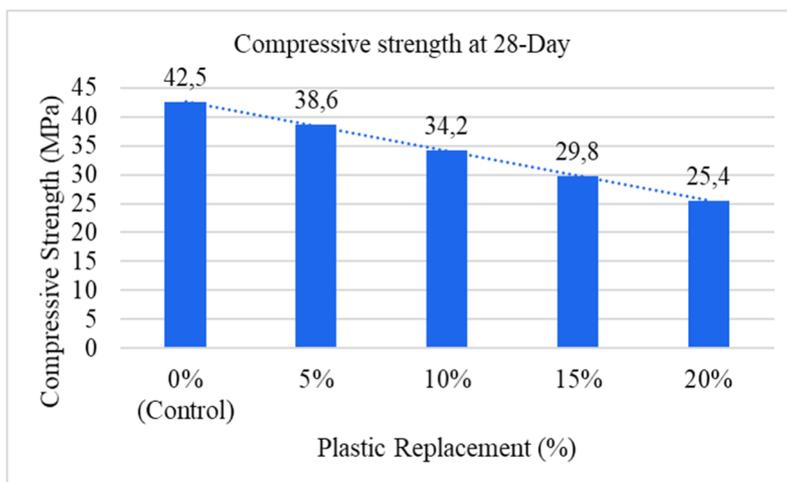


Fig. 6. Shows compressive strength at 28-day.

Also representing strength reductions of 9.2 %, 19.5 %, 29.9 %, and 40.2 % respectively as shown in the (Fig.7). The studies [14–17] also show that the incorporation of plastic waste as an aggregate replacement tends to degrade the strength performance

and workability of concrete, depending on the proportion of the replacement level. Oddo M.C. et al. [18] obtained a decreasing result by using 30% light-blue plastic flakes and plastic granules, approximately 47% and 62%, respectively, considering reference concrete.

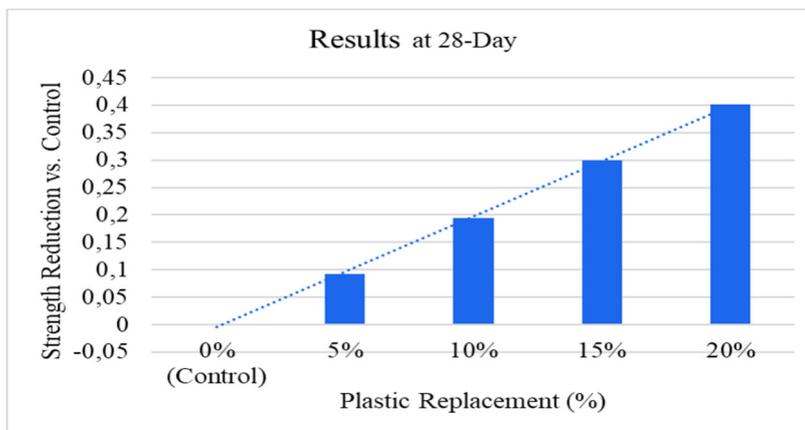


Fig. 7. Shows strength reduction at 28-day.

This strength reduction stems from both the weak plastic-cement interfacial bond, evidenced by SEM-observed gaps at the aggregate-mortar interface (Fig. 8), and increased matrix porosity from the non-absorbent plastic particles. The results suggest

that while  $\leq 10\%$  plastic replacement remains viable for non-structural applications, higher replacements require surface modifications or additives to mitigate strength losses while maintaining environmental benefits.

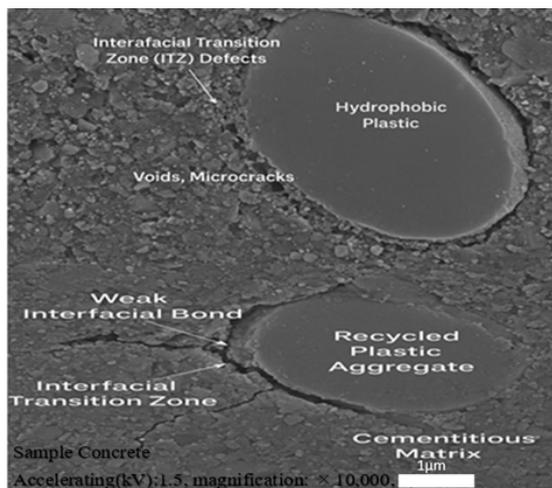


Fig. 8. Illustrates the plastic aggregate and mortar interfacial transition zone status determined with SEM analysis (JEOL JSM-IT300).

**Split tensile strength.** The split tensile strength was evaluated with plastic aggregate replacement, showing a progressive strength reduction as plastic content increased. The control mixes 0% plastic achieved a tensile strength of 3.8 MPa at 28 days, while replacement mixes demonstrated declining values: 3.5 MPa, 3.1 MPa, 2.7 MPa, and 2.3 MPa as shown in (Fig. 9), and representing strength reductions of 7.9 %, 18.4 %, 28.9 %, and 39.5 % respectively (Tab. 2).

On another hand, density was 2450, 2225, 2100, 2005, 1984 kg/m<sup>3</sup> respectively (Table 2). [19] found that the density of concrete decreased by 5 %, 8.7 %, and 10.71 % for 5 %, 10 %, and 15 % of replacement

respectively. Shubbar and Al-Shadeedi [20], found that the results indicated that at replacement level of 1, 2, 4, 8 % of plastic, there was a decrease of 0.5, 2.8, 7.3, 9 % in the density. This was because of the specific gravity of the PA was 13.75 % lower than fine aggregate. Also, Saikia and Brito [21], found that same results. The typical density of standard concrete ranges between 2200 to 2500 kg/m<sup>3</sup>, lightweight concrete ranges between 1400 to 1850 kg/m<sup>3</sup> and for high-density concrete from 2800 to 4000 kg/m<sup>3</sup> according to ASTM C138/C138M-14.

Ultrasonic Pulse velocity of cube specimens was measuring using ПУЛЬСАР-2.1 device. The recorded values of UPV were 5.65, 5.58, 5.52, 5.49,

5.45 km/s (Table 3). Related to the 0% PA the UPV showed reductions of 1.2% ,2.3% ,2.8% and 3.5% respectively.

Comparing to the results that Rahmani [22] recorded UPV values 5.35 km/s at 0 % PA, 5.30 km/s at 5 % PA, 5.25 km/s at 10 % PA, and 5.21 km/s at 15%

PA. However, no data was provided 20 % of PA replacement. Workability of the mixture, determined by slump test; by adding and increasing of PA, the rate of the slump was increased as shown in the (Fig. 10).

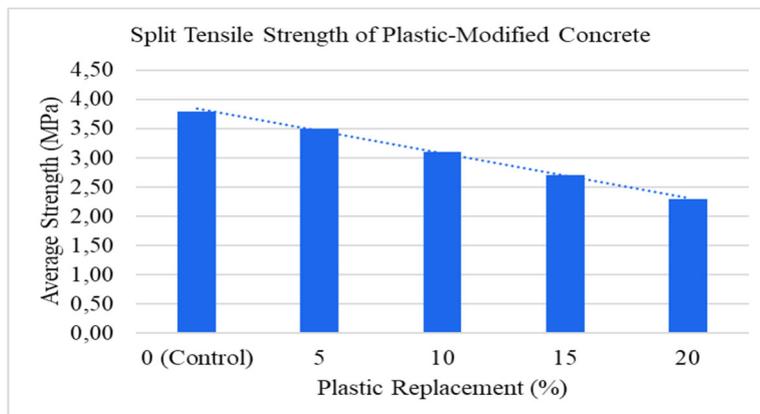


Fig. 9. Shows split tensile strength at 28-day.

Table 3

**Split Tensile Strength of Plastic-Modified Concrete**

Plastic Replacement (%)	Standard Deviation (MPa)	Strength Reduction (%)	Suitability Classification	Density kg/m <sup>3</sup>	Type of Concrete	Ultrasonic Pulse velocity of cube [km/s]
0 (Control)	±0.15	0%	Structural	2450	Standard Concrete	5.65
5	±0.12	7.90%	Structural	2225	Standard Concrete	5.58
10	±0.18	18.40%	Light Structural	2100	Lightweight Concrete	5.52
15	±0.14	28.90%	Non-Structural	2005	Lightweight Concrete	5.49
20	±0.16	39.50%	Non-Structural	1984	Lightweight Concrete	5.45

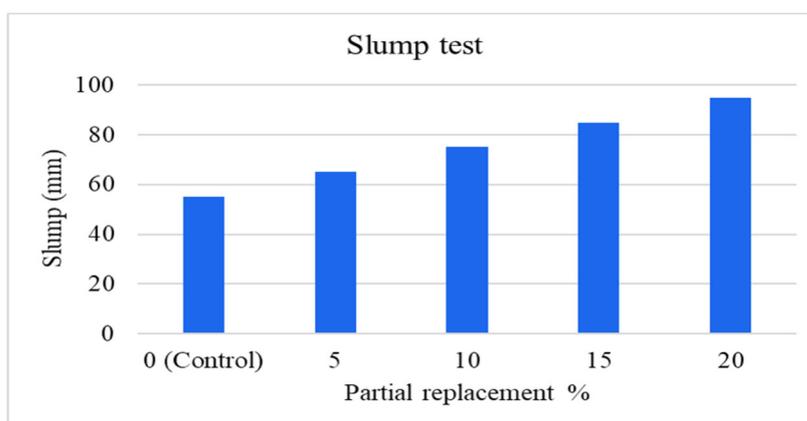


Fig. 10. Shows slump test.

**Flexural strength.** The control mix 0% plastic exhibited a flexural strength of 5.2 MPa at 28 days, while plastic-modified specimens showed declining performance: 4.8 MPa, 4.3 MPa, 3.7 MPa, and 3.2 MPa (Fig. 11), representing strength reductions of

7.7 %, 17.3 %, 28.8 %, and 38.5 % respectively. Concrete with higher replacement levels (15–20 %) is more suitable for non-structural applications with minimal flexural requirements, such as lightweight partitions or paving blocks, as shown in the Table 4.

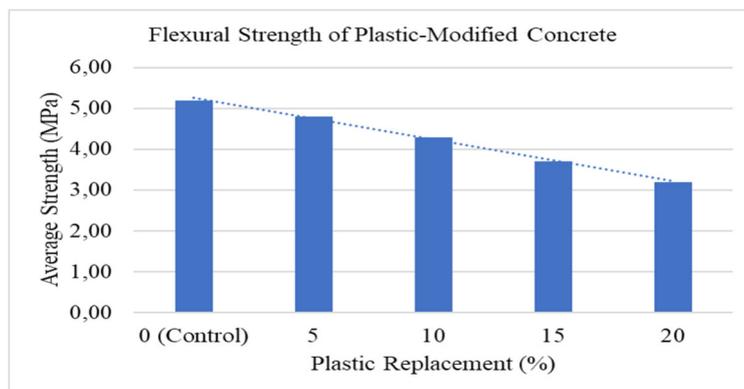


Fig. 11. Shows flexural strength at 28-day.

Table 4

**Flexural Strength of Plastic-Modified Concrete**

Plastic Replacement (%)	Standard Deviation (MPa)	Strength Retention (%)	Application Suitability
0 (Control)	±0.20	100%	Structural
5	±0.18	92.30%	Structural
10	±0.22	82.70%	Light Structural
15	±0.19	71.20%	Non-Structural
20	±0.21	61.50%	Non-Structura

The experimental results demonstrate a consistent reduction in mechanical properties with increasing plastic aggregate replacement. This proportional degradation across all strength parameters ( $R^2 > 0.95$ ) primarily stems from weak plastic-cement interfacial bonding and increased matrix porosity, as confirmed by SEM analysis. While  $\leq 10\%$  replacement maintained  $> 80\%$  of control strengths – suggesting viability for light structural applications – higher plastic contents require either performance-enhancing modifications or restriction to non-structural uses, though all mixes exhibited proper curing behavior and low strength variability ( $COV < 5\%$ ). These findings provide clear thresholds for sustainable concrete design using waste plastics while highlighting the need for interface engineering to mitigate strength losses. Azad A.M. et al. [23] also found that the reduction in modulus of rupture when using PVC aggregates was relatively lower compared to the losses observed in compressive strength and splitting tensile strength.

**Conclusions.**

This study investigated the effects of incorporating waste plastic (LDPE) as a partial replacement for fine aggregates in concrete in Jordan, evaluating its impact on compressive, split tensile, and flexural strengths. The key findings are summarized as follows:

**Mechanical Strength Degradation.** The inclusion of plastic aggregates resulted in a progressive reduction in strength properties. Compressive strength decreased by 9.2–40.2 %, split tensile

strength by 7.9–39.5 %, and flexural strength by 7.7–38.5 % as plastic replacement increased from 5 % to 20 %.

The linear correlation ( $R^2 > 0.95$ ) between strength loss and plastic content confirms that weak interfacial bonding and increased porosity are the primary degradation mechanisms. The mechanical strength degradation in LDPE-modified concrete primarily stems from weak interfacial bonding and increased porosity. LDPE's hydrophobic nature and smooth surface hinder adhesion with the cement matrix, while its low surface energy prevents chemical interaction with cement hydrates. As LDPE content rises, stress transfer weakens, linearly reducing strength. Additionally, LDPE's lower density and regular shape impair compaction, trapping air and creating micro-voids at the LDPE-cement interface, which act as crack initiation places.

**Threshold for Structural Viability:**

- $\leq 10\%$  plastic replacement maintained  $> 80\%$  of the control mix strength, making it suitable for light structural applications (e.g., partition walls, low-load pavements).
- $> 15\%$  replacement led to  $> 30\%$  strength loss, restricting its use to non-structural elements (e.g., thermal insulation blocks, lightweight panels).

**Microstructural Observations (SEM):**

- Interfacial Transition Zone (ITZ) defects (voids, micro-cracks) were prominent at higher plastic percentages, explaining the mechanical performance decline.

- Poor adhesion between hydrophobic plastic and cement paste was identified as the root cause of strength reduction.

#### Practical Recommendations:

- Concrete with a plastic replacement of  $\leq 10\%$  is used for structural applications with the surface treatments (e.g., acid etching) to enhance bonding.
- Higher replacements (15–20%) can be employed where strength is secondary to lightweight or thermal insulation benefits. For nonstructural uses.
- For future research, nano-additives or fiber reinforcement should be explored to mitigate strength losses at higher replacement levels.

The study result indicates that waste plastic may be sustainably recycled in concrete, albeit with restricted restrictions. While low-percentage replacements ( $\leq 10\%$ ) offer a balanced compromise between eco-efficiency and structural performance, higher doses require supplementary techniques to promote interfacial bonding. These findings help to green construction practices by offering actionable instructions for plastic waste usage in concrete technology.

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Поступила 06.07.2025 г.

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## МЕХАНИЧЕСКОЕ И МИКРОСТРУКТУРНОЕ ПОВЕДЕНИЕ БЕТОНА С ОТХОДАМИ ПЭНП В КАЧЕСТВЕ ЧАСТИЧНОЙ ЗАМЕНЫ МЕЛКОГО ЗАПОЛНИТЕЛЯ

**Аннотация.** Утилизация пластиковых отходов представляет собой серьезную глобальную экологическую проблему из-за рисков для здоровья, высоких затрат на утилизацию и сложности управления свалками. Несанкционированный сброс усугубляет проблему, подчеркивая необходимость в экологически устойчивых решениях для повторного использования. Следовательно, существует острая необходимость в изучении альтернативных методов повторного использования пластиковых отходов для других целей, и бетон был определен как один из жизнеспособных вариантов использования пластиковых отходов в качестве части заполнителя бетона. Следовательно, целью данного исследования является иллюстрация использования полиэтилена низкой плотности (ПЭНП) в Иордании в качестве частичной замены мелкого заполнителя в бетоне марки 40 МПа и оценка его влияния на механические и физические свойства бетона на основе 0 %, 5 %, 10 %, 15 % и 20 % процента заменяемого пластика. Путем приготовления и испытания пяти различных бетонных смесей с заменой ПЭНП при водоцементном отношении (В/Ц) 0,4. Включение пластиковых заполнителей привело к последовательному снижению механических свойств с увеличением замены пластиковых заполнителей, где прочность на сжатие снизилась с 42,5 МПа (0 %) до 25,4 МПа (20 %), прочность на растяжение при

расколе – с 3,8 МПа до 2,3 МПа, а прочность на изгиб – с 5,2 МПа до 3,2 МПа, показав максимальное снижение на 40,2 %, 39,5 % и 38,5 % соответственно. Таким образом, пластик является одним из экологически чистых материалов, который может быть использован в качестве частичной замены мелких заполнителей в бетоне в Иордании.

**Ключевые слова:** механические свойства бетона, добавки полиэтилена (ПЭНП), частичная замена мелкого заполнителя, микроструктурное поведение бетона, пластиковые отходы.

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*Received 06.07.2025*

#### **Для цитирования:**

Обейд М.А.А., Абу-Махади М.И., Насрат Н.А.Г. Механическое и микроструктурное поведение бетона с отходами ПЭНП в качестве частичной замены мелкого заполнителя. *Вестник БГТУ им. В.Г. Шухова*. 2026. № 3. С. 21–31. DOI: 10.34031/2071-7318-2026-11-3-21-31

#### **For citation:**

Obeid M.A.A., Abu-Mahadi M.I., Nasrat N.A.G. Mechanical and microstructural behavior of concrete with LDPE waste as partial fine aggregate replacement. *Bulletin of BSTU named after V.G. Shukhov*. 2026. No. 3. Pp. 21–31. DOI: 10.34031/2071-7318-2026-11-3-21-31