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# MECHANICAL PROPERTIES OF LIGHTWEIGHT CONCRETE WITH RECYCLED EPS AND POLYPROPYLENE FIBERS

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## ABSTRACT

*Lightweight concrete is increasingly utilized in sustainable construction due to its reduced weight and improved thermal performance. However, replacing conventional aggregates with alternative lightweight materials may result in a reduction in concrete strength. To address this issue, fiber reinforcement has been introduced to enhance the concrete's overall mechanical behavior. This study examines the mechanical properties of concrete mixes incorporating recycled expanded polystyrene (EPS) granules and polypropylene (PP) fibers. The effect of replacing crushed aggregate with EPS was evaluated by comparing a reference mix with mixes including 25 % and 50 % EPS replacement by volume. Additionally, the influence of fiber reinforcement was assessed by comparing a mix with 50 % EPS with mixes containing 0.5 % and 1.0 % fiber by volume. Key properties including density, flexural strength, compressive strength, and dynamic modulus were measured at 7 and 28 days. At 7 days, replacing conventional aggregate with 25 % EPS reduced density by approximately 21 %, flexural strength by 34 %, compressive strength by 57 %, and dynamic modulus by 37 % relative to the reference mix. A 50 % EPS substitution further lowered these properties by approximately 36 %, 54 %, 67 %, and 57 %, respectively. At 28 days, the relative reductions remained consistent. Adding fibers to the 50 % EPS mix improved flexural performance: a 0.5 % fiber dosage increased flexural strength by roughly 10 % at 7 days and 13 % at 28 days, while a 1.0 % dosage increased it by about 28 % at 7 days and 24 % at 28 days. The incorporation of fibers had minimal impact on density, compressive strength, and dynamic modulus.*

## 1. INTRODUCTION

Reducing energy consumption for heating and warming is crucial for enhancing building energy efficiency. Conventional concrete, the most important building material, exhibits limited thermal insulation performance due to its high thermal conductivity, generally between 0.6 and 3.2 W/m·K. On the other hand, lightweight concrete typically exhibits thermal conductivity values between 0.4 and 1.89 W/m·K, while insulating concrete with polystyrene beads or a cellular structure can achieve as low as 0.07 to 0.33 W/m·K [1]. Properly composed, lightweight concrete could prevent thermal bridges by ensuring a continuous insulating layer and, with its low thermal conductivity and durability, further enhance energy efficiency and building performance [2]. These high-thermal insulating materials are formulated using lightweight aggregates, such as expanded polystyrene (EPS), cork, expanded clay, or silica aerogel [3]. EPS is a lightweight, inert thermoplastic material composed of approximately 98 % air, widely utilized in packaging and thermal insulation applications [4]. Unmodified EPS exhibits a cellular microstructure characterized by closed-cell membranes composed of expandable polystyrene (PS), with typical densities below 50 kg/m³ [5]. Currently, EPS is recycled in at least 38 countries, encompassing a population exceeding 4.2 billion people across four continents [6]. Incorporating EPS as a lightweight aggregate in concrete mixtures has been shown to reduce density and thermal conductivity. However, the reduction in density negatively impacts mechanical properties, including compressive, flexural, and tensile strength [7]. Fiber reinforcement is widely recognized as an effective technique to enhance the tensile performance and energy absorption capacity of cement composite structures [8]. Synthetic fibers manufactured from petroleum products, particularly polypropylene fibers (PP), are favored due to their low cost, ease of application, high strength-to-weight ratio, and excellent chemical resistance. PP fibers are also known for their resistance to acids and alkalis, which makes them suitable for use with various types of Portland cement. Their simple production and ease of integration into concrete mixes result in improved performance by effectively inhibiting the propagation of microcracks, reducing permeability, and enhancing strength [9-11].

While a significant body of research has focused on lightweight concrete and on polypropylene fiber-reinforced concrete separately, relatively few studies have explored the combined use of lightweight aggregates and fibers. This study aims to evaluate the mechanical performance of lightweight concrete incorporating both recycled EPS granules and PP fibers, with the aim of developing sustainable construction solutions that balance weight reduction and structural integrity.

## 2. MATERIALS AND METHODS

The samples were prepared using Portland cement type CEM IV/B-W 32.5 N, limestone aggregate with a bulk density of 1600 kg/m³ (with the particle size distribution provided in Table 1), and tap water. The EPS granules were prepared by manually crushing a 50-mm thick board and then sieving the material through a 4.0-mm mesh. The bulk density of EPS granules was 12.97 kg/m$^3$. The PP fibers (SikaFiber PPM-12), with a density of 0.91 g/cm³, and length of 12 mm ± 1 mm were used in this study. Table 2 details the composition of the concrete mixes used in this study. The designation R refers to the reference mix, which does not include any EPS or fibers. In the R1 mix, one-quarter of the limestone aggregate volume is replaced by EPS granules, while in the R2 mix, half of the limestone aggregate is substituted with EPS granules. The PP1 mix comprises equal volumes of limestone and EPS aggregates with an addition of 0.5 % polypropylene fibers by volume, whereas the PP2 mix, also containing equal volumes of limestone and EPS aggregates, incorporates 1.0 % polypropylene fibers by volume.

To evaluate the impact of substituting crushed aggregate with EPS granules mixes R, R1, and R2 were designed to ensure consistent workability across all variations. Since the incorporation of EPS reduces the water demand of the mix, a lower water content was employed to achieve the targeted consistency. To assess the effect of PP fiber addition, the mix designs for mixtures R2, PP1, and PP2 were formulated with the fiber volume fractions 0 %, 0.5 %, and 1.0 %, respectively. The content of fibers is calculated by multiplying its volume by its density, according to the equation:

$$Mas.\%\,PP = \left(\frac{Vol.\%PP \times 1m^3}{100}\right) \times 910\,\frac{kg}{m^3} \qquad \text{...... (1)}$$

The cement, aggregate, and fibers were initially mixed for 30 seconds, after which water was added and blended for another 60 seconds. Once a viscous mix was achieved, EPS granules were gradually introduced into the running mixer in portions to prevent overspill, with the complete addition taking 60 seconds. Finally, the mixture was blended for 180 seconds before being discharged for fresh state testing and specimen production, resulting in a total mixing time of 5 minutes and 30 seconds. After mixing, the consistency of all fresh concrete specimens was evaluated following BAS EN 12350-2 [12]. The consistency test results are shown in Table 2, as well. The samples were then cast into metal molds to form cubes (100×100×100 mm) and prisms (40×40×160 mm) for further testing. Finally, the specimens were immersed in water maintained at 20 ± 2 °C until testing.

*Table 1. Particle size distribution of aggregate*

| Particle size (mm) | Total passing (%) |
|---|---|
| 8 | 100 |
| 6.3 | 99.1 |
| 4 | 97.71 |
| 2 | 65.38 |
| 1 | 46.99 |
| 0.7 | 34.53 |
| 0.5 | 28.96 |
| 0.25 | 21.38 |
| 0.125 | 16.52 |
| 0.063 | 13.09 |
| 0 | 0.00 |

*Table 2. Composition of concretes and fresh concrete consistency*

| Component | R | R1 | R2 | PP1 | PP2 |
|---|---|---|---|---|---|
| Cement (kg/m³) | 412.5 | 412.5 | 412.5 | 411.2 | 409.9 |
| Aggregate (kg/m³) | 1650 | 1237.5 | 825 | 822.4 | 819.5 |
| EPS (kg/m³) | - | 2.50 | 5.0 | 4.97 | 4.97 |
| PP Fibers (kg/m³) | - | - | - | 4.55 | 9.10 |
| Water (kg/m³) | 206.3 | 198.08 | 173.3 | 172.7 | 172.3 |
| Total (kg/m³) | 2268.8 | 1850.6 | 1415.8 | 1415.8 | 1415.8 |
| Fresh Concrete Consistency (cm) | 6.0 | 8.0 | 7.0 | 5.0 | 3.0 |

After curing, the concrete specimens were subjected to a series of tests to evaluate their mechanical and physical properties: compressive strength (BAS EN 12390-3) [13], flexural strength (BAS EN 12390-5) [14], water-saturated density (BS EN 12390-7) [15], and dynamic modulus of elasticity (BAS EN 12504-4) [16].

## 3. RESULTS AND ANALYSIS

The experimental program was designed to distinguish the effects of aggregate replacement and fiber reinforcement. The impact of substituting crushed aggregate with EPS granules was evaluated by comparing mixes R, R1, and R2, while the influence of PP fibers incorporation was assessed by examining the differences between mixes R2, PP1, and PP2. The experimental results are presented in Tables 3–6. Table 3 summarizes the water-saturated density measurements for all specimens at both 7 and 28 days, providing insights into the changes in density over time. Table 4 details the flexural strength values, while Table 5 presents the compressive strength results for the same curing periods. Finally, Table 6 reports the dynamic modulus of elasticity, highlighting the stiffness characteristics of the concrete mixtures.

*Table 3. Water-saturated density of concrete*

| Sample | Density - 7 days (kg/m$^3$) | Density - 28 days (kg/m$^3$) |
|---|---|---|
| R | 2.32 | 2.39 |
| R1 | 1.83 | 1.86 |
| R2 | 1.48 | 1.50 |
| PP1 | 1.46 | 1.48 |
| PP2 | 1.45 | 1.47 |

*Table 4. Flexural strength of concrete*

| Sample | Flexural strength - 7 days (MPa) | Flexural strength - 28 days (MPa) |
|---|---|---|
| R | 4.25 | 5.10 |
| R1 | 2.80 | 3.30 |
| R2 | 1.95 | 2.70 |
| PP1 | 2.15 | 3.05 |
| PP2 | 2.50 | 3.35 |

*Table 5. Compressive strength of concrete*

| Sample | Compressive strength - 7 days (MPa) | Compressive strength - 28 days (MPa) |
|---|---|---|
| R | 16.8 | 39.15 |
| R1 | 7.3 | 24.2 |
| R2 | 5.5 | 14.9 |
| PP1 | 5.15 | 15.4 |
| PP2 | 5.6 | 14.75 |

*Table 6. Dynamic modulus of concrete*

| Sample | Dynamic modulus - 7 days (GPa) | Dynamic modulus - 28 days (GPa) |
|---|---|---|
| R | 31.09 | 45.68 |
| R1 | 19.58 | 25.21 |
| R2 | 13.48 | 17.10 |
| PP1 | 11.73 | 15.61 |
| PP2 | 12.49 | 15.50 |

Figure 1 displays concrete specimens after compressive strength testing, illustrating the internal structure when EPS granules and PP fibers are incorporated. Figure 2 presents a chart that summarizes the impact of these modifications on the properties of hardened concrete.

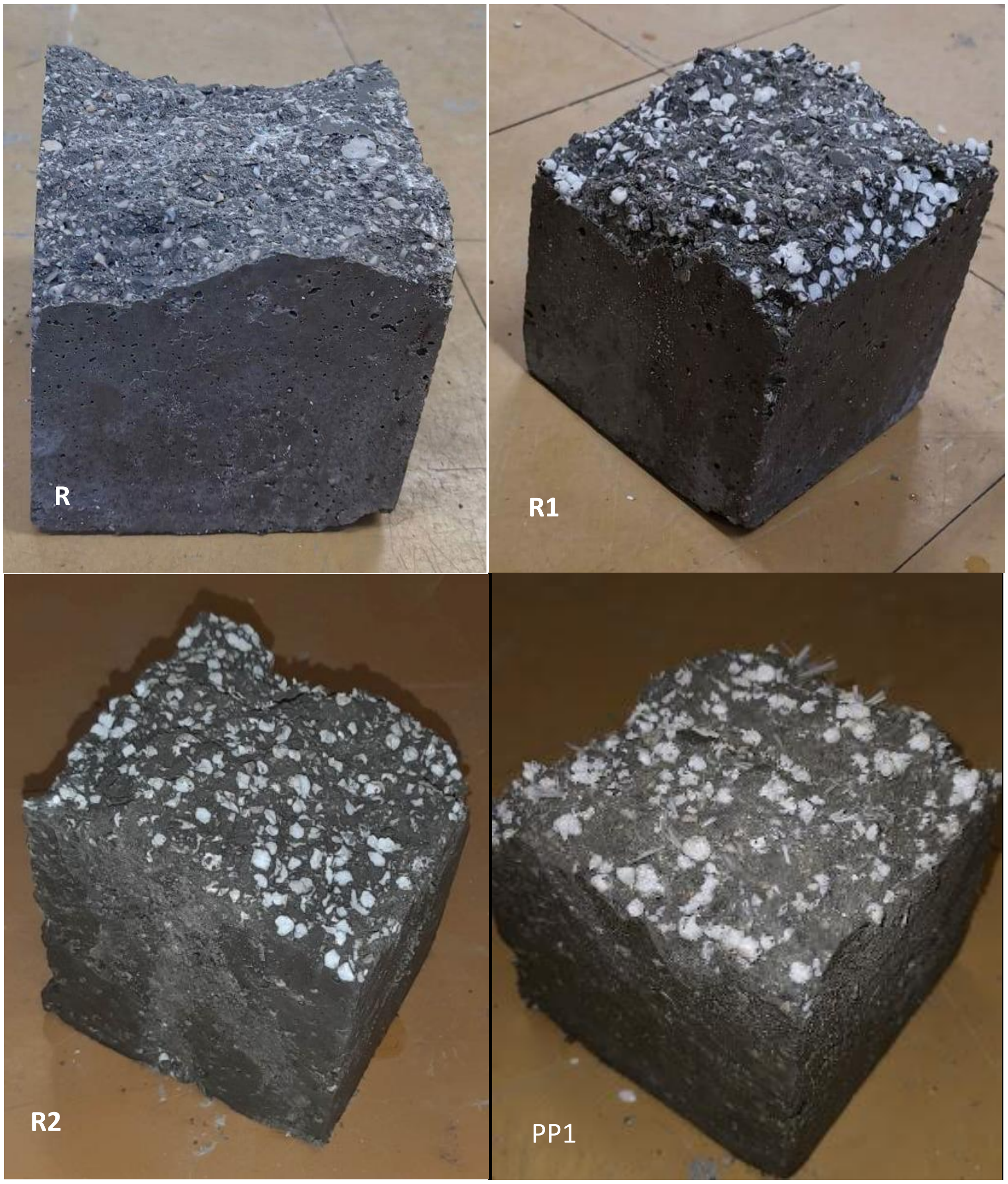

Figure 1. Concrete samples after the compressive strength test

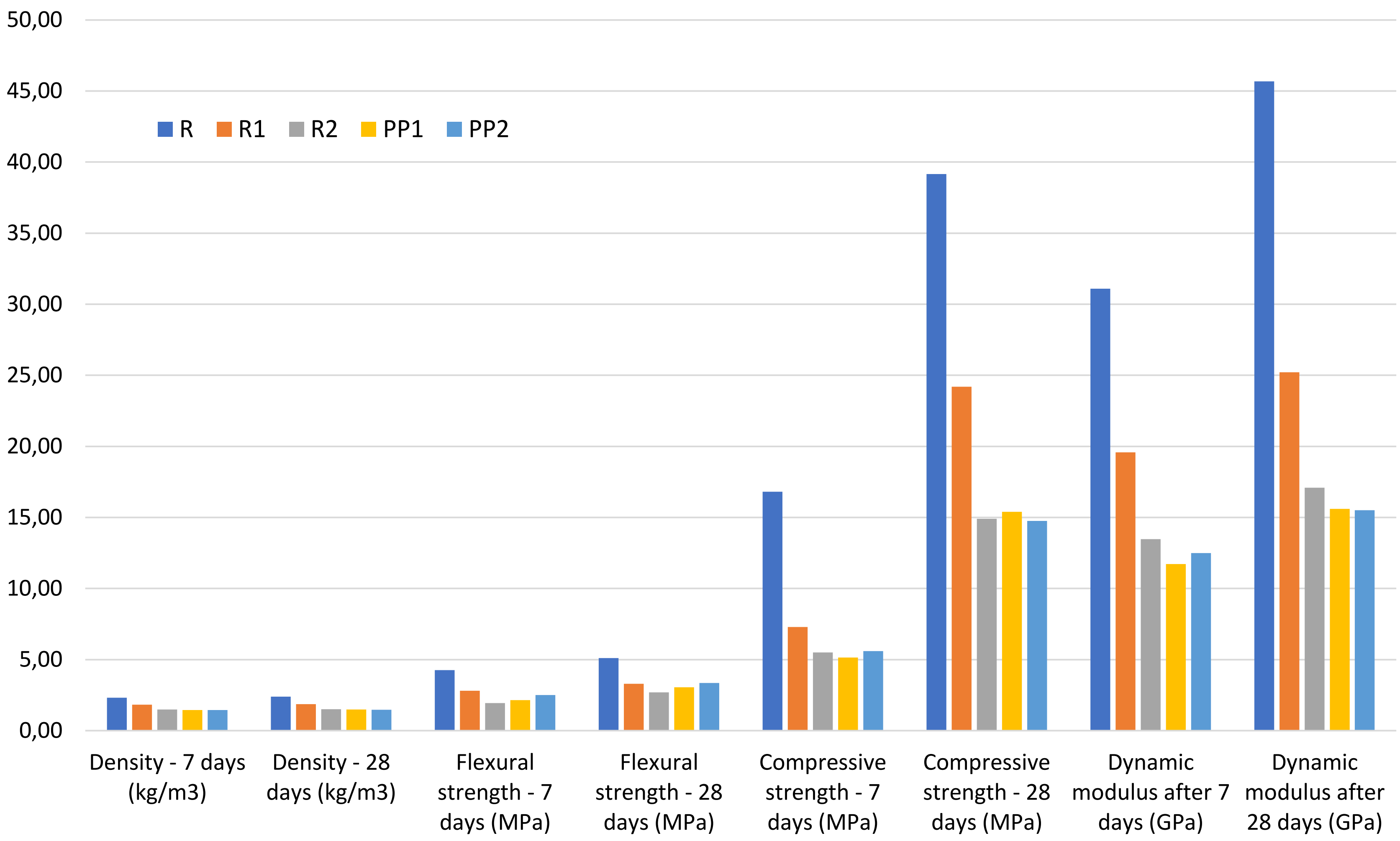


*Figure 2. The effect of EPS granules and PP fibers on hardened concrete properties*

The results indicate that substituting crushed aggregate with EPS granules leads, due to the lightweight nature of EPS, to a reduced density accompanied by a corresponding decline in mechanical performance. At 25 % EPS substitution (R1), the density at 7 days decreases by approximately 21 % compared to the reference mix (R), and by around 36 % at 50 % EPS (R2). Compared to the reference mix (R), a 25 % EPS replacement (R1) decreased flexural, and compressive strengths, and dynamic modulus by roughly 34 %, 57 %, and 37 % at 7 days, with similar trends observed at 28 days. A further increase to 50 % EPS replacement (R2) led to additional reductions of about 54 %, 67 %, and 57 % in these properties relative to R, which can be attributed to the low density, weak bonds between EPS granules and concrete matrix, and inferior stiffness of EPS compared to traditional aggregates. Additionally, the effect of fiber addition was evaluated by comparing R2 with fiber-reinforced mixes (PP1 and PP2). The incorporation of fibers concrete containing 50 % EPS as an aggregate replacement had minimal impact on density, compressive strength, and dynamic modulus. However, fiber reinforcement notably enhanced flexural performance. At 7 days, a 0.5 % fiber addition (PP1) increased flexural strength by approximately 10 % compared to R2, while a 1.0 % fiber addition (PP2) improved it by about 28 %. A similar trend was observed at 28 days. This improvement is likely due to the fibers' ability to bridge cracks and enhance tensile behavior, thus mitigating some of the mechanical losses associated with lightweight aggregates. In contrast, the effect of fibers on compressive strength was minimal, reflecting that fiber reinforcement predominantly benefits tensile-related properties rather than compressive behavior. The dynamic modulus decreased slightly with fiber addition, likely due to local discontinuities introduced by the fibers.

## 4. CONCLUSIONS

This study demonstrates the potential of valorizing recycled EPS in conjunction with PP fibers to produce lightweight concrete. Our results indicate that replacing conventional aggregates with EPS granules effectively decreases water-saturated density by approximately 21 % at 25 % replacement and 36 % at 50 % replacement, while leading to significant reductions in both flexural and compressive strengths, as well as in dynamic modulus. To counteract these adverse effects, the incorporation of PP fibers was investigated. Although fiber addition had little impact on density, compressive strength, and modulus, it notably enhanced flexural performance—improving flexural strength by up to 28 % with a 1.0 % fiber dosage. It is important to note that this study focused solely on the mechanical properties of the concrete mixes; thermal properties, which are crucial for energy efficiency, were not investigated. Future research should focus on optimizing the interfacial bonding between EPS and the cementitious matrix, further refining fiber dosage and distribution, and extending the investigation to include thermal performance. Such studies will be essential for developing sustainable, high-performance lightweight concrete formulations that meet the rigorous demands of modern structural applications.

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