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The Influence of Heating Temperature on Aggregates Made from Expanded Polystyrene on the Mechanical Behaviors of Lightweight Concrete

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ABSTRACT

The use of lightweight materials is currently increasing because it is able to reduce the weight of structures and, of course, will provide a smaller seismic load. Efforts to minimize the burden of lightweight materials can be achieved by substituting conventional aggregates with lighter alternatives, such as EPS. The utilization of EPS not only helps in reducing structural loads but also serves as a solution to address plastic waste pollution. This study aims to improve the quality of lightweight concrete using pumice sand and aggregates from EPS waste. The concrete quality was improved by improving the aggregate performance of EPS waste by heating. Heating of EPs waste aggregates was carried out at temperature variations of 100℃, 110℃, 120℃, 130℃, 140℃. The composition of the cement-soil mixture was made in volume ratios of: 1 part cement, 2 parts pumice sand and 3 parts modified EPS aggregate with a water cement ratio of 0.45. The quality tests carried out include compressive strength test, tensile strength test and collapse modulus test. The results of this study indicate that the increase in EPS density due to the applied heating has an impact on the improvement of the mechanical parameter values of lightweight concrete.

1. INTRODUCTION

Lightweight concrete is a type of concrete that contains lightweight aggregate and has an equilibrium density not exceeding 0.135 kcf, as determined by ASTM C567 [1]. It can be categorized into various types, such as no-fines concrete, lightweight aggregate concrete, and aerated/foamed concrete. Lightweight aggregate concrete uses porous lightweight aggregates with low specific gravity, either natural or artificial, resulting in a low specific gravity for the concrete itself [2]. These lightweight aggregates reduce the overall density of the concrete, making it significantly lighter than traditional concrete. Additionally, the reduced weight of lightweight concrete can lead to cost savings in transportation and handling [3]. Furthermore, the lower density of lightweight concrete enhances its thermal properties, making it an ideal choice for buildings requiring insulation [4]. Due to its versatility and durability, lightweight concrete has become increasingly popular in the construction industry. With advancements in technology, the strength and performance of lightweight concrete continue to improve, making it a sustainable and efficient option for various construction applications. As the demand for sustainable building materials grows, lightweight concrete is expected to play a significant role in the future of constructions world.

Tidore Island, located in North Maluku, holds significant potential for pumice stone extraction. The extent of pumice reserves on Tidore Island is evident from the thickness of the exposed layers in various mining areas as shown in Figure 1. Pumice is a natural material with promising potential as a lightweight construction material [5]. The use of lightweight construction materials can reduce the overall weight of structures, thereby minimizing seismic loads [6].

Recently, on Tidore Island, pumice in the form of pumice sand is being utilized as a partial replacement for sand in the production of lightweight concrete bricks (batako). Notably, research results suggest that pumice sand from Tidore Island can be used as a material for lightweight precast concrete bricks meeting to the Indonesian National Standard (SNI) spesification [7]. Beyond its application in lightweight bricks, pumice can also serve as a substitute for some or all of the coarse aggregates to create lightweight concrete. The use of pumice from Tidore Island as aggregate produces lightweight concrete with a significant reduction in weight [7, 8]. Nevertheless, in comparison to other lightweight materials like Hebel bricks in the market, pumice-based lightweight concrete remains relatively heavier.

The efforts in developing lightweight concrete continue to evolve. In addition to the use of naturally lightweight materials, the utilization of lightweight materials from industrial waste is also increasingly common, such as the use of Expanded Polystyrene (EPS) materials. Furthermore, the utilization of EPS waste as lightweight concrete is expected to reduce environmental pollution caused by plastic waste. Weight reduction of concrete can significantly be improved by using EPS as aggregate in concrete [9], where the Lightweight concrete produced from EPS weights as little as one-fifth the weight of cement bricks [10]. Utilisation EPS in the form of granules or aggregates can be used as a substitute for part or all of the sand in the concrete block mixture [11-13], and as a substitute for coarse aggregate in concrete [14, 15]. Increasing the amount of EPS aggregate in concrete or brick showed a decrease in weight and compressive strength [10-11]. Further, in order to achieve the standard quality of the bricks, the use of EPS aggregate should not exceed 50% of the aggregate volume [11]. When 100% EPS is utilized as a coarse aggregate in concrete, the result is concrete that is extremely lightweight but also of notably low quality [16, 17].

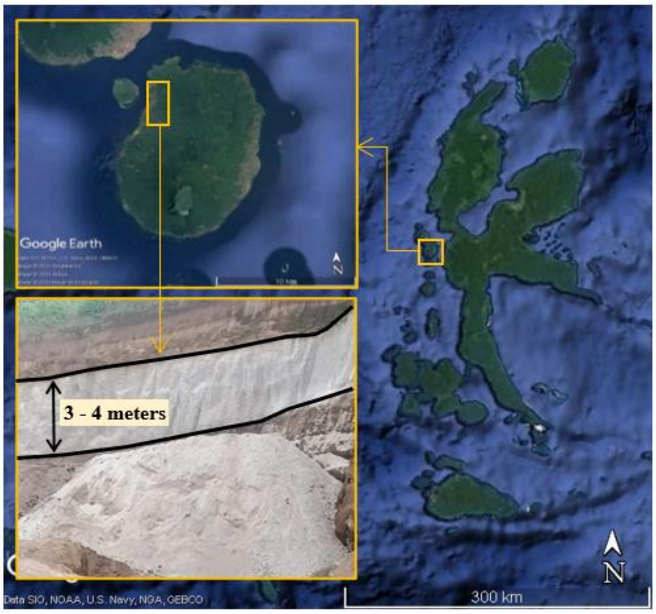

Figure 1. Pumice stone sand quarry on Tidore Island

Efforts to improve the quality of lightweight concrete can be made by adding additives, such as: epoxy resin, foaming agent [18, 19] or modification of the aggregates used, such as: bio-based aggregate, limestone [20, 21]. Despite their effectiveness, these options incur high expenses and the results exhibits notably low strength characteristics. In order to improving the quality of aggregates, recently, several techniques for enhancing quality have been suggested, such as: crushing, heat treatment, carbonization, and the strengthening by using chemicals material [22]. Subjecting EPS aggregate to heat can alter its characteristics and enhance its compressive strength, rendering it suitable for incorporation into concrete production [23]. Heat treatment of discarded EPS foams can yield modified EPS aggregates suitable for use in lightweight concrete with increased compressive strength.

Pumice and EPS waste aggregates are two common types of lightweight aggregates used in producing lightweight concrete. Pumice, a volcanic rock, is both lightweight and porous, making it an effective insulator and fire retardant [24]. EPS waste aggregates, on the other hand, are made from recycled expanded polystyrene foam, which is lightweight and provides excellent thermal insulation properties [25]. Incorporating these waste aggregates into lightweight concrete mixes can further enhance the already impressive advantages of using lightweight concrete. For instance, by substituting traditional aggregates with pumice and EPS waste aggregates in a lightweight concrete slab for a building's flooring, the structure can benefit from improved energy efficiency and reduced heating and cooling costs. Moreover, utilizing these waste aggregates aids in diverting materials from landfills, promoting a more sustainable and environmentally friendly construction process.

Based on these studies, it was deemed necessary to conduct this study in order to utilize local materials and modified EPS waste to produce lightweight concrete with better quality and environmentally friendly. However, the present study only focuses on the effect of temperature in the process of modifying coarse aggregate from EPS waste and its impact on the mechanical value of pumice sand lightweight concrete produced. This research also has not discussed the resistance of lightweight concrete to environmental factors, thermal conductivity, and cost effectiveness.

2. RESEARCH METHOD

2.1 Materials preparation

The materials employed in this study encompassed a range of components essential for concrete production, including fine aggregate, coarse aggregate, cement, and water. The fine aggregate component specifically utilized pumice sand, which was meticulously sourced from pumice mines located on Tidore Island. To ensure its suitability for the intended application, the pumice sand underwent a screening process to achieve the specified sand size in accordance with the standards outlined in SNI 03-2847-2002. On the other hand, the coarse aggregate segment of the concrete mixture was composed of artificial aggregate derived from EPS waste. This EPS waste was sourced from various sources, including electronic packaging, fish packaging, and residues from fishing activities predominantly found in Ternate city.

The process of preparing the artificial aggregate involved cutting the EPS waste into manageable pieces to form aggregates, which were then subjected to a carefully controlled heating process in an oven. This modification process of EPS waste aggregate follows the method detailed by Kan & Demirboga [26]. The test results indicate that the density of EPS (Expanded Polystyrene) material exhibits a consistent behavior up to a temperature of 100℃. To create the modified EPS aggregate, the heating process involves temperatures of 110℃, 120℃, 130℃, and 140℃, each maintained for a duration of 15 minutes. This carefully controlled heating regimen is crucial for altering the properties of the EPS material, enhancing its suitability for applications such as lightweight concrete production.

2.2 Lightweight specimens

The composition of the concrete mix was made in volume measurements as done by Ala and Arruan [27] which used 1 part cement, 2 parts fine aggregate, 3 parts coarse aggregate. This mixture uses a cement water ratio of 0,45. The mixing process used a concrete mixer. Lightweight concrete specimens were made in the form of cylinders and beams. Testing the compressive and tensile strength of concrete using cylindrical specimens of 150 mm diameter, 300 mm height while testing the flexural strength using beam specimens of 150 mm width, 150 mm height and 600 mm length. All specimens were treated by immersion in a water bath for 27 days. The day before testing, the specimens were removed from the immersion bath and dried.

2.3 Testing methods

Specimen testing to determine the mechanical characteristics of concrete adheres to the guidelines set by the Indonesian National Standard (SNI). This includes the compressive strength test, which is crucial for assessing the quality of concrete [28], the split tensile strength test used to ascertain the tensile strength of concrete [29], and the flexural strength test employed to determine the modulus of concrete collapse [30]. Detailed procedures for conducting each characteristic test are presented in Figure 2.

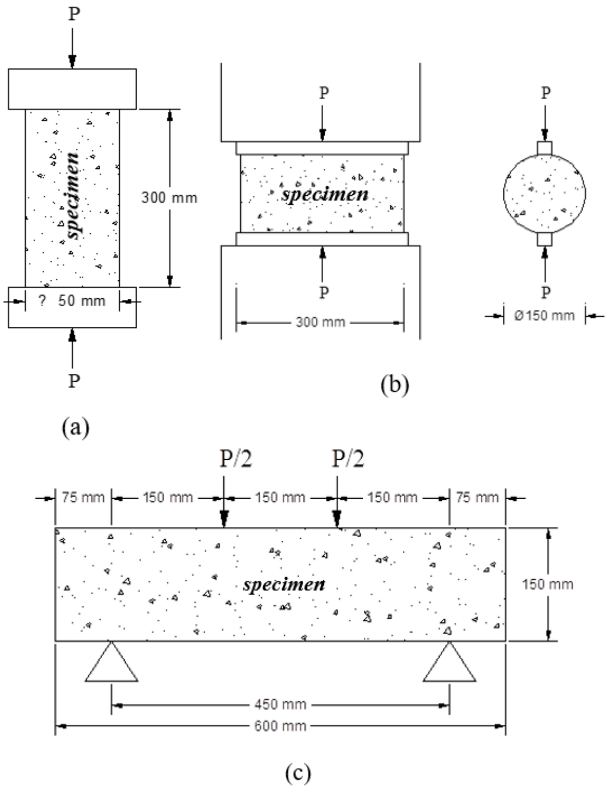

Figure 2. Concrete characteristic testing scheme, a) compressive strength test, b) split tensile test, c) flexural strength test

3. RESULTS AND DISCUSSION

3.1 Characteristics of fine aggregate

The results obtained from testing the characteristics of fine aggregates, conducted in accordance with SNI standards, are detailed in Table 1. The analysis indicates that pumice sand possesses properties typical of lightweight materials, including elevated water content and water absorption rates. These findings provide conclusive evidence supporting the assertion that pumice sand exhibits high levels of porosity. The significance of these results lies in their implications for concrete production, particularly in the formulation of lightweight concrete mixes. The highly porous nature of pumice sand suggests that it can contribute to the overall lightweight properties of concrete, making it an attractive option for applications requiring reduced structural weight without compromising strength. Additionally, the findings underscore the importance of understanding the specific characteristics of fine aggregates in optimizing concrete mix designs for various construction needs.

3.2 EPS aggregate depreciation

The coarse aggregate size of Styrofoam waste in this study was determined to be between 10 mm and 20 mm. To achieve this size, pieces of Styrofoam with dimensions of 20×20×18 mm^3, 25×25×25 mm^3, 35×30×30 mm^3 and 40×37.5×37.5 mm^3 were heated respectively at temperatures of 110℃, 120℃, 130℃ and 140℃ for 15 minutes. The results of heating the Styrofoam pieces produce new sizes of 14×15×13 mm^3, 14×15×15 mm^3, 16×15×14.5 mm^3, and 17.5×15×15 mm^3. The change in aggregate volume of EPS waste due to heating can be seen in Figure 3.

Table 1. Recap of fine aggregate (Pumice sand) test results

Characteristics	Testing Standards	Result	Specifications
Sludge content	(SNI ASTM C117:2012)	12.83	0.2-5.0%
Water content	SNI 1971:2011	30.39	3.0-5.0%
Volume weight (Solid state)	SNI-03-4804:1998	1.14	1.6-1.9 kg/ltr
Volume weight (Loose condition)	SNI-03-4804:1998	1.03	1.6-1.9 kg/ltr
Absorption (Water absorption)	SNI 1970:2008	43.30	0.2 - 2.0 %
Oven dry specific gravity	SNI 1970:2008	0.98	1.6-3.2 %
Surface dry specific gravity (SSD)	SNI 1970:2008	1.53	1.6-3.2 %
Modulus of fineness	SNI ASTM C136:2012	3.66	1.5-3.8%

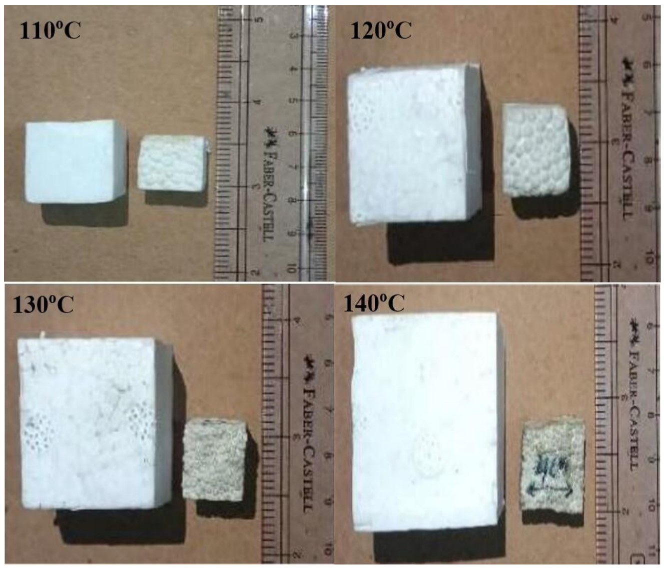

Figure 1. Volume change of EPS aggregate due to heating

In Figure 3, it can be seen that the size of the EPS pieces before heating is different to produce the same aggregate size after heating. The higher the temperature, the larger the size of EPS before heating. The magnitude of the change in volume of EPS can be seen in Figure 4.

The shrinkage of EPS aggregate is calculated based on the difference between the volume before heating and after heating with the volume before heating. The amount of shrinkage of the EPs aggregate depends on the density of the EPS waste [9]. The higher the density of EPS waste, the smaller the shrinkage that occurs. The test results show that there is a considerable volume change until the heating temperature of 130℃. When compared between 110℃ and 120℃ heating temperatures, there was a shrinkage difference of 17.76%, between 120℃ and 130℃ of 9.11% and between 130℃ and 140℃ of 4.05%. The results show that the shrinkage rate of aggregates up to 130℃ is very high, but after passing temperatures greater than 130℃, the shrinkage rate decreases and tends to be constant.

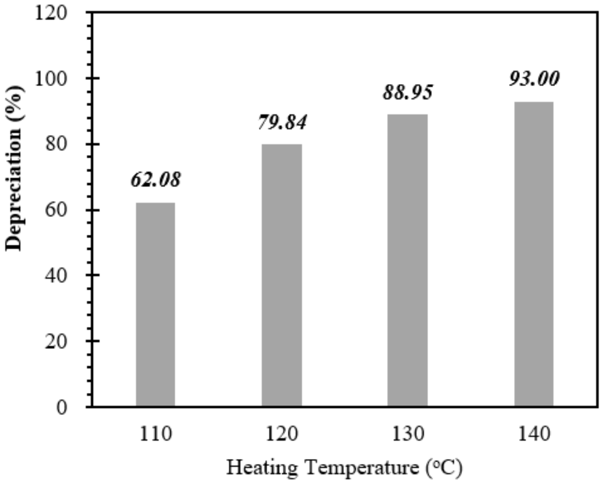

Figure 4. Volume shrinkage of Styrofoam aggregate

3.3 Density of EPS aggregate

The volume weight is calculated based on the weight of the aggregate in the container divided by the volume of the container. In the calculation of volume weight, all the modified EPS aggregates with various heating temperatures have a uniform size of between 10 mm and 20 mm. Heating causes the EPS aggregates to shrink which results in reduced volume and increased volume weight. Volume weight of aggregates.

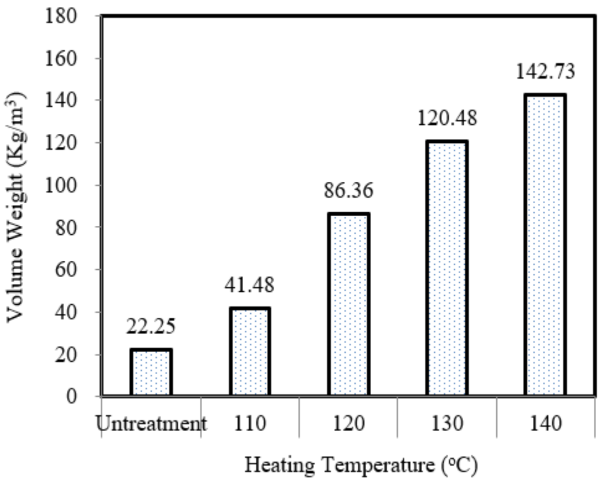

Figure 2. Density of modified EPS aggregate

The volume weight of the modified EPS aggregate showed an increase with the heating temperature. The largest increase in volume weight occurred from 110℃ to 120℃, followed by 120℃ to 130℃, and finally from 130℃ to 140℃ as shown in Figure 5. These results indicate that there is a directly proportional relationship between the shrinkage rate and the volume weight of the aggregates.

3.4 Workability of fresh concrete

Lightweight concrete is formed from pumice sand, modified EPS aggregate, cement, and water. All materials were mixed in a concrete mixer according to the volume measurements. The fresh concrete mix looked rather dry and lacked scuffs. The results of fresh concrete testing showed slump values between 10 mm and 20 mm as shown in Figure 6.

The low slump value observed in the concrete mix may be attributed to two primary factors. Firstly, the small self-weight of the aggregates can lead to minimal consolidation or settlement within the fresh concrete mix. This means that the aggregates do not settle significantly under their own weight, resulting in a less fluid mixture. Secondly, the use of pumice sand, known for its high porosity and water absorption characteristics, allows water to be readily absorbed into the aggregate. This absorption process can lead to a more viscous mixture, as the water is retained within the pores of the pumice sand rather than contributing to the fluidity of the mix. These factors combined can result in a concrete mix with a low slump value, indicating a less fluid and more cohesive mixture.

Figure 6. a) fresh lightweight concrete mix b) slump value

3.5 Distribution of modified EPS aggregate in concrete

One of the problems in the use of lightweight materials in concrete mixes is the low flowability of fresh concrete at low water cement ratio (wcr) values which can lead to uneven distribution of aggregates. In concrete mixtures with high wcr values or the use of diluents can make the aggregates float and concentrate at the surface during the mixing and compacting process. The grain distribution of the modified EPS aggregate can be seen in Figure 7.

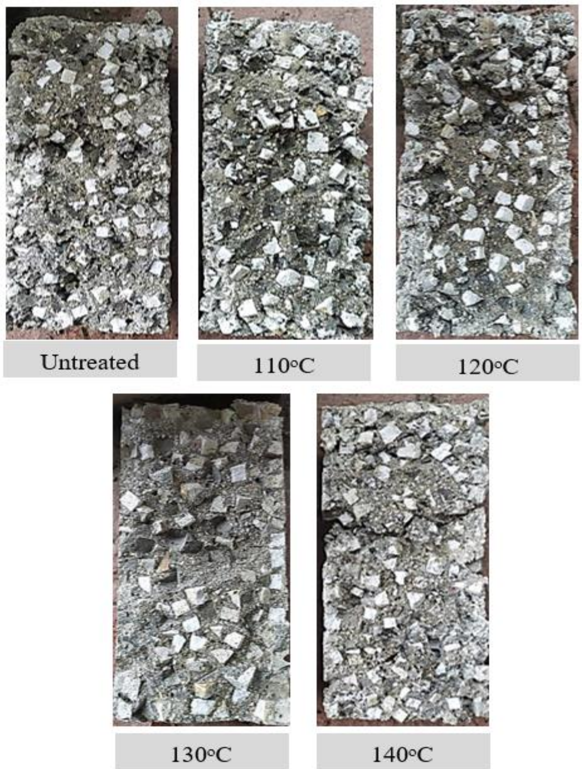

Figure 3. Distribution of modified EPS aggregate in concrete

Figure 7 shows that the distribution of EPS aggregate in the concrete is quite even. It can be seen that the amount of EPS at the top and bottom is almost the same. This indicates that the mixing process was done well. It can also be seen that the change in volume weight of the aggregates due to heating has little effect on the distribution of aggregates in the lightweight concrete.

3.6 Concrete volume weight

The volume weight of concrete is obtained from the measurement of the weight of the concrete cylinder. The volume weight of concrete for each increase in heating temperature of EPS aggregate can be seen in Figure 8.

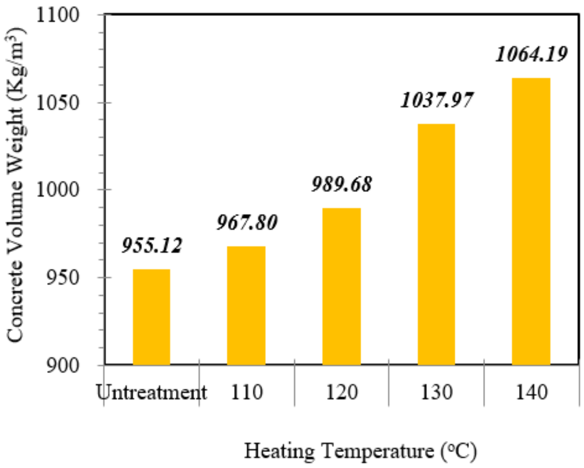

Figure 8. Lightweight concrete density

Figure 8 shows that the higher the heating temperature in the process of making modified EPS aggregate, the greater the volume weight of concrete produced. This result is in line with the increase in weight of the modified EPS aggregate due to the increase in heating temperature as shown in Figure 5. The lightweight concrete using unheated EPS and pumice sand is 27.92% lighter than the previous study using EPS and ordinary sand at the same composition [27].

3.7 Mechanical characteristics of concrete

The mechanical characteristics of concrete are obtained from SNI standard tests, in the form of testing compressive strength, split tensile and flexural strength. The results of testing the mechanical characteristics of concrete can be seen in Figure 9.

When compared to previous research [27], The unheated EPS lightweight concrete using aggregate from pumice sand presented has a lower compressive strength. This indicates that the pumice sand only acts as a weight reducing agent in the concrete.

Figure 9 shows that the compressive strength, tensile strength and flexural strength show an increase as the heating temperature of the aggregates increases. Significant improvement in the mechanical characteristics of concrete is seen with the use of EPS aggregates heated up to 130°C. The mechanical characteristics of concrete using EPS aggregates heated beyond 130°C show little improvement and are more likely to remain constant. The effect of heating the Eps aggregate is quite influential on the quality of lightweight concrete with pumice sand as fine aggregate, however the quality of this concrete is lower when compared to the use of modified Eps and ordinary sand in the concrete mixture in previous research [23]. This also strengthens the assumption that pumice sand with high porosity tends to be brittle.

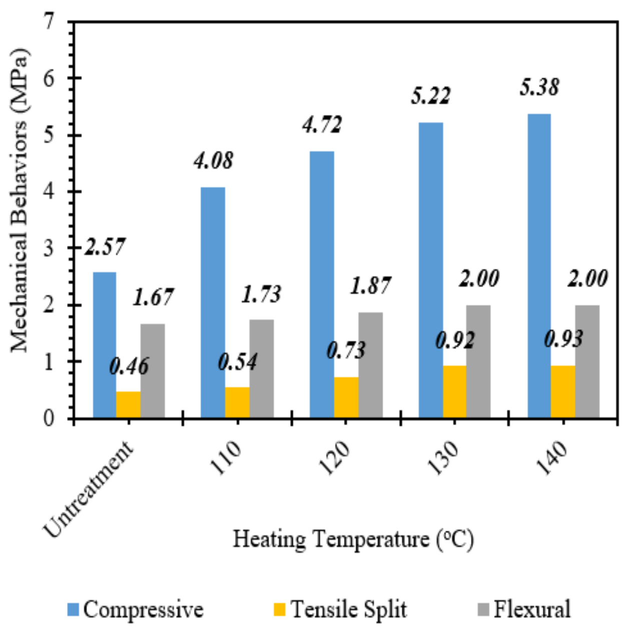

Figure 4. Mechanical characteristics of modified EPS lightweight concrete

The relationship between tensile strength and flexural strength to compressive strength is represented by a value of $\sqrt{f_c'}$. The analysis, employing curve fitting as a simple regression method, reveals a correlation between tensile strength and flexural strength with the compressive strength value, denoted as $f_{ct} = 0.35\sqrt{f_c'}$ and $f_r = 0.88\sqrt{f_c'}$ where f'_c, f_{ct} and f_r are in MPa. The split tensile strength value shows compliance with American Concrete Institute (ACI) standards [31] for lightweight concrete while the flexural strength value shows a higher value.

4. CONCLUSIONS

Based on the test results, heating aggregates from EPS waste can enhance the quality of lightweight aggregates, with higher temperatures yielding better-quality aggregates. Additionally, modifying EPS waste into coarse aggregate significantly improves the mechanical characteristics of the resulting lightweight concrete. However, concrete mixes using aggregates from pumice sand and EPS heated to 140°C only produce low-grade (non-structural) concrete. These findings emphasize the critical role of heating temperatures in improving lightweight aggregate quality and the consequential impact on concrete properties.

The results also highlight the potential of EPS waste as a valuable resource in producing high-quality lightweight concrete. The modification process significantly enhances properties such as compressive strength, flexural strength, and durability. However, it is essential to carefully consider the processing and utilization of EPS waste, as evidenced by the limitations observed at higher heating temperatures. These findings underscore the importance of thoughtful material selection and processing methods in optimizing concrete performance.

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