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Post-Fire Mechanical Properties of Concrete Incorporating Waste EPS (Styrofoam) as Aggregate Replacement

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Abstract: Reusing waste is one of the most recent topics and one of the main contributors to sustainability. It is known that concrete is one of the most common materials to produce different types of construction members around the world. That is due to mainly its low cost, availability, long period of durability, and ability to withstand harsh environments. On the other hand, due to the rapid changes that have happened in the last few decades in the production of decorative materials, some material types of cladding are used for decoration purposes, such as Styrofoam (EPS) (trade name "Astropol"), which is developed from disposal materials. Discovering and implementing a method of reusing these wastes in concrete is beneficial for the environment to reduce waste around the globe. In the current study, Styrofoam (Astropol) waste was used as a replacement for fine aggregate since concrete structures contain this material in their composition. It is important to test these materials for fire resistance and expose them to an elevated temperature in order to discover the post-fire mechanical properties of the composite material. The experimental result showed that the post-fire compressive strength of concrete containing different ratios of EPS (Astropol) increases compared to conventional concrete. The compressive strengths were 19.94 MPa, 19.295 MPa, 16.806 MPa, and 17.66 MPa for 0%, 15%, 25%, and 50%, respectively, while the post-fire indirect tensile strength for all specimens containing EPS reduced as the fire duration and temperature increased.

Keywords: post-fire mechanical property; EPS (Astropol) waste; compressive strength; split tensile strength

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1. Introduction

Reinforced concrete can be exposed to high temperatures, such as fire, or in some locations, a concrete structure is used when a firing process is being undertaken. This may cause a deterioration in the concrete's properties. One of the most important physical properties is to decay the loss in compressive strength, the loss of an elastic modulus, and the cracking and spalling of the concrete. It also caused a reduction in the yield strength, ductility, and tensile strength of the steel, and the loss of a bond between concrete and steel [1,2]. Many studies have been conducted on materials characterization and their recycling in the construction sector [3]. As a result, this has led to a decrease in the use of certain materials which have been replaced with waste materials, which is the main reason and source for producing engineering-based wastes.

There are many studies on the characterization and modelling of normal and high-strength concrete in terms of its compressive strength properties where conventional aggregates were used [4–6]. These materials have their disadvantages and advantages in reinforced or hybrid frame structures [7–9]. As the old structure ages, it requires adequate retrofitting and strengthening in order to resist external loads [10,11]. Therefore, this structural system could be strengthened with suitable materials to resist any external forces which affect the structure. Developing such innovative materials in materials science would assist in improving structural properties, such as concrete with plastic aggregates, which shows a great performance in experimental testing and modelling behavior [12,13].

For any materials that become waste, then, it is possible for them to be recycled by changing their form by grinding, melting, or milling them. For example, engineered-based wastes, such as concrete, brick, tile, ceramic, glass, plastic, bituminous mixture, pipe, decorative materials, etc. When each of these materials become waste, they can be recycled in one of the following ways mentioned above and utilized in an engineering field, such as the utilization of plastic and glass wastes in producing composite concrete [14].

There has been much research conducted to investigate the contributions and the effect of waste in concrete. For example, plastic, rubber, EPS, glass, and waste concrete exists as well. These studies investigated the intensely different hardened and fresh properties of concrete after using waste materials [15,16].

Idris [17] studied the behavior of foam concrete with polypropylene fiber and Styrofoam. The Styrofoam was used in three different diameters, 2–3 mm, 3–4 mm, and 5–6 mm, and with different Styrofoam percentages by volume fraction; they were 10%, 20%, and 30%. The results showed that the use of these materials has increased the compressive strength and the flexural strength of the foamed concrete, especially in the use of 3–4 mm of Styrofoam of a 10% volume and 0.8 kg/m^3 of Polypropylene fiber given the highest compressive strength, and the use of 2–3 mm of Styrofoam of a 10% volume and 0.8 kg/m^3 of Polypropylene fiber given the highest flexural strength.

Wibowo [18] conducted research on a concrete wall panel from Styrofoam waste with a wire mesh reinforcement. The Styrofoam concrete wall panel was constructed (length = 1 m, width = 0.3 m, and thickness = 0.07 m) with the addition of 0.015 m thick plaster/mortar on both sides. Styrofoam was used with a 60% fine aggregate volume, and the experimental results showed that the wall panel with 60% of Styrofoam and wire mesh increased the flexural strength of the wall panel.

Herbudiman et al. [19] conducted an experiment on the mechanical properties of concrete with the substitution of coated Styrofoam balls with coarse aggregate. The coating materials were made by mixing Portland cement and RCC-15 as the pozzolanic material, and the Styrofoam balls of a 20 mm diameter were used by substituting the coarse aggregate by 5%, 15%, and 20%. The compressive strength test, split-tensile strength test, and flexural strength test were conducted, in which the results of the compressive strength of 5%, 15%, and 20% provided 27.6 MPa, 24.3 MPa, and 20.3 MPa, respectively, the splitting tensile strength provided 2.5 MPa, 2.2 MPa, and 1.7 MPa, respectively, and the flexural strength provided 5 MPa, 4.5 MPa, and 3.8 MPa, respectively. These results revealed that different amounts of the coarse aggregate Styrofoam balls in concrete are applied to achieve adequate structural strength, and the Styrofoam ball substitution content can be also increased to make lightweight structural members.

Solikin and Ikhsan [20] and Solikin et al. [21] studied Styrofoam as a partial substitution of fine aggregate in lightweight concrete and self-compacting concrete bricks. The Styrofoam was used in ratios of 0%, 30%, 40%, and 50%, replacing the fine aggregate, then the compressive strength test, flexural strength test, and water absorption test were conducted. Reductions were observed in all the results of compressive strength, flexural strength, weight, and volume. However, despite the reductions, the results confirmed that using Styrofoam as a substitution for a fine aggregate of up to 50% replacement is suitable and meets the standards of concrete brick.

Mahdi et al. [22] also studied the manufacturing and improving the characteristics of the isolation of concrete composites by adding Styrofoam particles. Experimental studies and investigations were conducted on the thermal and mechanical properties of lightweight concrete by using Styrofoam balls in different volumes (0%, 8%, 16%, and 32%). The results showed that the compressive strength of the concrete decreased by 12%; however, it increased the thermal conductivity by 30%, and this was a reason to reduce the mass of the cast composite of concrete.

Abduh [23] studied the effect of Styrofoam waste on the compressive strength of normal concrete with the addition of Glenium. Styrofoam of 10% and 1% of Glenium was used in the mix and it achieved a compressive strength of 27.64 MPa, and the same percent of Glenium and 20% of Styrofoam achieved a compressive strength of 20.09 MPa; for 30% of Styrofoam, the compressive strength reduced by 16.20%.

Vieira et al. [24] studied the post-fire residual mechanical properties of concrete made with recycled concrete coarse aggregates; therefore, it was decided to use recycled coarse aggregate in this study. In this study, one concrete mix was used with natural coarse aggregate, and three different concrete specimens with different ratios of recycled coarse aggregate was used. The ratios were 20%, 50%, and 100%, and they were replaced with natural coarse aggregate. After 1 h of exposure of fire in 400 °C, 600 °C, and 800 °C, there was not any significant difference between the effect of natural and recycled aggregate in concrete after being exposed to fire.

Marques et al. [25] studied the post-fire residual mechanical properties of concrete made with recycled rubber aggregate (RRA) at 5%, 10%, and 15% by replacing both fine and coarse aggregate with RRA. Specimens were exposed to 400 °C, 600 °C, and 800 °C for 1 h. The results showed that mixes with RRA were more affected than conventional concrete, which means that the compressive strength, tensile strength, and flexural strength were gradually decreased for the specimens containing RRA.

Astropol is a commercial brand name that is used for the decoration purpose of houses, buildings, skyscrapers, and multistory buildings. The Astropol materials are composed of Styrofoam and deep-sea sand, in which the sandy beach is used as the protective layer to protect the underlying Styrofoam surface.

Due to the changes that have occurred in the last few years in the production of decoration materials, some types of decorative materials have become applicable to be used in purposes besides decoration. This is the case for Styrofoam (Astropol) due to the huge variety of different alternatives available that will change Astropol from the most used decorative material to an engineered-based waste.

This study investigates the pre- and post-fire mechanical properties of fresh concrete with and without the addition of Astropol to the concrete mix. Since structural members exposed to fire behave differently, it is crucial to understand the behavior of concrete containing this type of waste material after it has been exposed to fire. With the increasing amount of waste, Astropol must become a mechanism to reduce, recycle, and reuse those wastes and reduce the impact on the environment.

Astropol in this research is used as a fine aggregate replacement for normal aggregate, and the results will be compared to the conventional concrete specimens. To investigate the effect of fire exposure on concrete containing EPS waste, the concrete mix proportion was 1:0.75:1.5 and the water/cement ratio was 0.45 for all the specimens. The ratios of Astropol waste used in the concrete mix as a fine aggregate replacement were introduced by volume fractions of 0%, 15%, 25%, and 50%.

2. Materials and Methods

The total number of concrete cylindrical specimens used was 36, and they were prepared at 0%, 15%, 25%, and 50% (with a 100 mm diameter × 200 mm high). In the following sections, the basic properties of the essential ingredients used, their mix proportioning, specimen preparation, and fire exposure arrangement will be explored in detail.

2.1. Materials Prepartion

Ordinary Portland Cement (Type 1) is manufactured locally according to EN 197-1:2011 [26] with a strength of 25 MPa. Fine aggregates were naturally obtained from medium river sand with a maximum size of 4.75 mm, a loose dry density of 1322 kg/m^3, and a saturated specific gravity of 2.59. Coarse aggregates (max. size = 10 mm) were also brought from the river with a saturated specific gravity of 2.64.

Styrofoam (Astropol) was used in two different forms because Styrofoam (Astropol) is composed of two layers; see Figure 1. One layer of deep-sea sand and one layer of EPS were used. Both layers were separated and ground, and they were then used as a fine aggregate substitution in the concrete mixes.

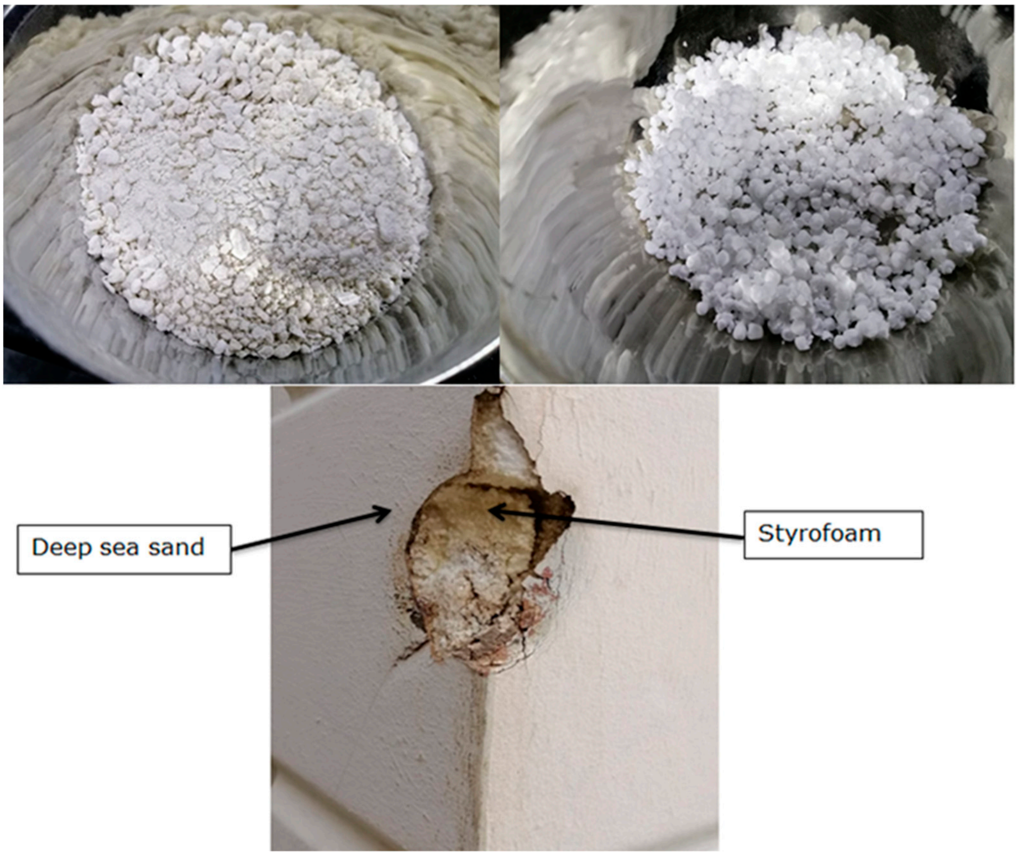

Figure 1. Astropol and the composing layers.

In addition, normal tap water was used. Particle size distributions of both fine and coarse aggregates were conducted according to BS EN 12620 (2002) [27], as shown in Figures 2–4.

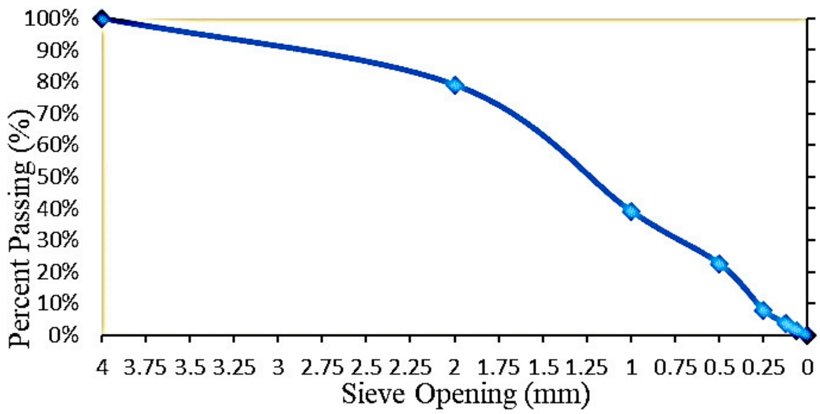

Figure 2. Fine aggregate particle size distribution.

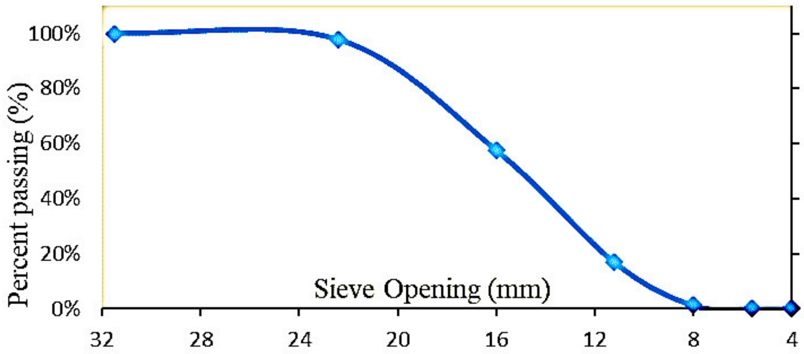

Figure 3. Coarse aggregate particle size distribution.

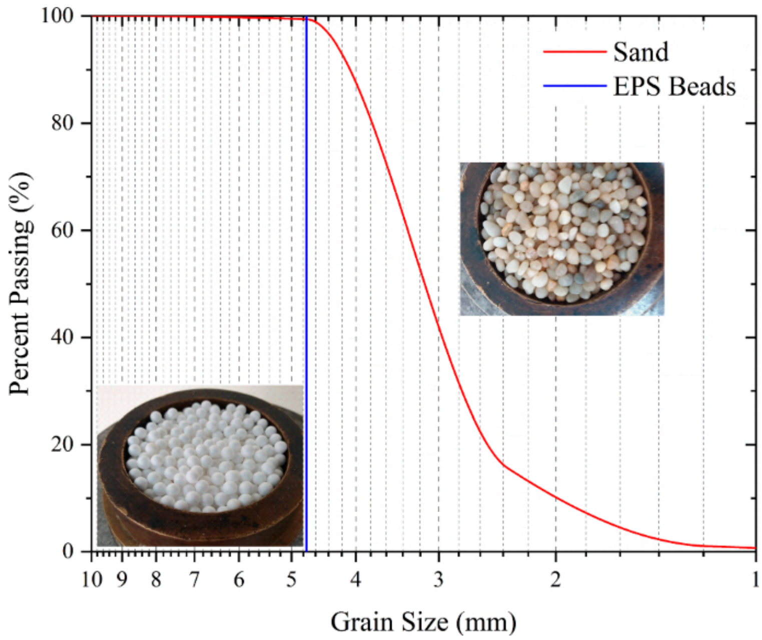

Figure 4. Particle size distribution of EPS and deep-sea sand. Reprinted are adopted with permission from ref. [28]. Copyright 2022, Springer Nature.

2.2. Mix Proportions

For the practical work, four various mixes with different mix proportions were prepared to make the specimens. Fine aggregates in the first mix were used without EPS waste, whereas in the other three mixes, EPS waste was used to partially replace the fine aggregates. The EPS waste contents were 15%, 25%, and 50% by weight of the fine aggregate. The parameters of the concrete components found in material tests were used to make the first mix proportion following an accordance to ACI 211.1 [29]. The maximum range of the slump (80 mm–140 mm) was targeted to save the adequate workability of other mixes. The anticipated mean compressive strength for the concrete mix was 25 MPa. The specific gravities of both fine and coarse aggregates were 2.64 and 2.59, respectively. Consequently, the concrete mix proportions were 1:0.75:1.5:0.45 by weight for cement fine aggregate, coarse aggregate, and water cement ratio, respectively. The density of the EPS was measured, and the replacement was conducted by weight of the fine aggregate. Since the density of the fine aggregate is incomparably greater than the density of EPS, the specified weight in each percentage is taken and specifically converted to the volume at each replacement level. The values shown in the volumetric mix table for the EPS are the volume converted to the weight in gm.

In order to guarantee a sufficient amount of concrete to prepare the specimens in the exact volume of concrete required as per the volume of the molds, the amount was increased by 10% to be on the safe side. The w/c ratio was the same for all five mixes. Furthermore, the weights of cement, water, and coarse aggregates were constant in each mix in Table 1.

Table 1. Volumetric properties of the mix.

Weight of Constituent Materials in the Mix for One Cylinder (D = 10 cm, H = 20 cm)					
EPS Waste %		**0%**	**15%**	**25%**	**50%**
Material		**Amount (gm)**			
Cement		695.98	695.98	695.98	695.98
Fine aggregate		852.94	848.66	845.81	838.672
Coarse aggregate		1812.46	1812.46	1812.46	1812.46
Water		313.191	313.191	313.191	313.191
Astropol	EPS waste	0	0.547	0.912	1.824
	Deep-sea sand	0	3.733	6.222	12.444

2.3. Specimen Preparation and Curing

The concrete mixes were prepared following ASTM C685/C685M-17 [30]. The materials were weighted for each mix using a sensitive scale. The dry ingredients were placed in a steel tray; then, the aggregates and EPS wastes were completely dry mixed until the EPS waste was visually seen to be thoroughly mixed with the aggregates. After that, the cement is mixed with the aggregates in a dry condition and the water was finally added. The batching took approximately 10 min from mixing until the fresh concrete was prepared to be homogeneous. All molds (cubes and cylinders) were cleaned and lubricated, then the concrete was placed in the two layers. The specimens were cast on a vibrating table and each layer of concrete was compacted for about (5–10) seconds. After the vibration, the specimens were left to dry and set at standard room temperature. The specimens were removed from the molds after 24 h and cured for 28 days in a water tank, after which they were taken out from the water and then dried in a laboratory at an air temperature of 20 °C before being exposed to fire. It is worth mentioning that the values presented as the results are the average of the three specimens prepared at each EPS percentage.

2.4. Fresh Concrete Tests

The properties of the fresh concrete mix were determined as can be seen in Table 2 below. The density of fresh concrete was measured following ASTM C642-21 [31]. The slump test is the most commonly used method of measuring the consistency of concrete, which was measured by following ASTM C 143/C 143M [32], and the compacting factor was determined following BS EN 12350-4:2009 [33].

Table 2. Fresh properties of the concrete mix.

Properties of Fresh Concrete Mix				
Mix Proportion (%)	**0%**	**15%**	**25%**	**50%**
Density kg/m^3 (before burning)	2657.8	2646.1	2643.3	2630.57
Density kg/m^3 (after burning)	2567.66	2558.76	2554.54	2526.19
Compaction factor test	0.992	0.964	0.96	0.978
Slump test (mm)	128	95	83	105

2.5. Specimen's Firing Procedure

The firing procedure was followed to determine the effect of fire on the behavior and post-fire properties of concrete specimens made of EPS waste.

After 28 days of curing the specimens inside the water tank, the specimens were taken out and placed inside the kiln. The kiln used was created for burning materials and has the dimensions of (1.0 m × 2.0 m). The kiln temperature capacity could reach up to 1000 °C.

After putting the specimens inside the kiln, the temperature of the kiln gradually increased within one hour until the temperature inside the kiln reached 826 °C, as is shown in Figures 5 and 6. After one hour of burning, the specimens were taken out and left to cool down to room temperature.

Figure 5. Specimen firing inside the kiln for 1 h.

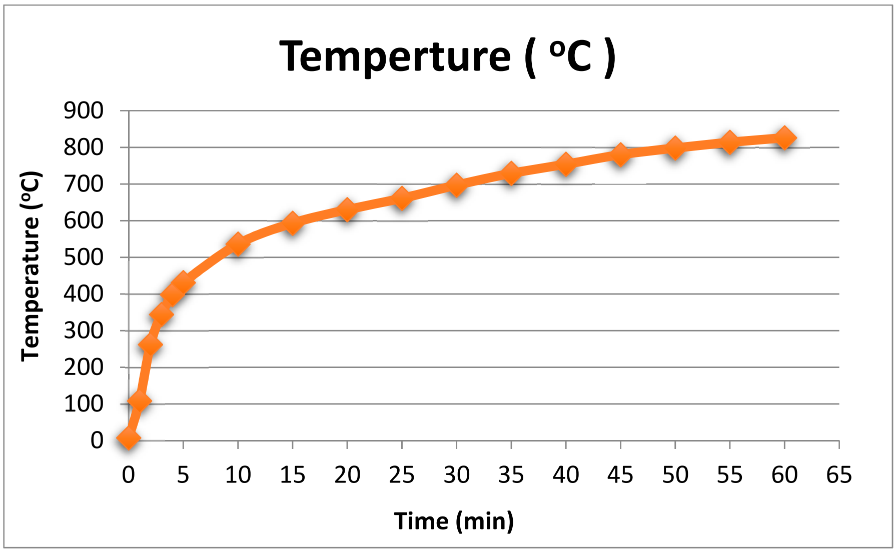

Figure 6. Temperature increment in the firing procedure within 1 h.

3. Results and Discussion

3.1. Compaction Factor Test

The compaction factor test was conducted for all of the different mixes, and the results are shown in Figure 7. The compaction factor results are derived from the compaction factor formula:

$$\text{Compaction factor} = (W_2 - W_1)/(W_3 - W_1)$$

where W_1 = weight of empty cone, W_2 = weight of partially compacted concrete, and W_3 = weight of fully compacted concrete.

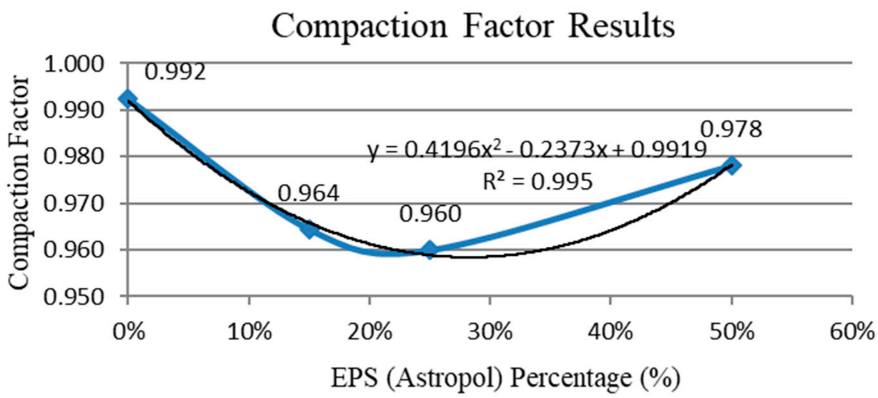

Figure 7. Compaction factor test result.

According to BS EN 12350-4:2009 [33], the degree of workability of all different concrete mixes is high because the compaction factors are higher than 0.92. The conventional concrete with 0% Astropol had a compaction factor of 0.992, and the concrete with 15%, 25%, and 50% had compaction factors of 0.964, 0.96, and 0.978, respectively. Since the compaction factor values are very close to each other when the EPS at three different percentages are added, although slight change can be seen, since the change is not significant, it can be said that the addition of EPS at these three different percentages does not significantly affect the compaction factor of conventional concrete.

3.2. Slump Test

The slump test was conducted for all concrete mixes, and the slump test is one of the factors which was used to determine the workability of concrete mixes. According to ASTM C143/C143M—05a [32], the conventional concrete mix and the concrete mix with 0% and 50% of EPS (Astropol) had a high workability (of 12.8 cm and 10.5 cm), respectively, because a slump result between 10 cm and 15 cm means that the degree of workability is high according to ASTM C143/C143M—05a [32]. The slump results of 15% and 25% of Astropol in the concrete mix had slump results of 9.5 cm and 8.3 cm, respectively; also, according to ASTM C143/C143M—05a [32], these concrete mixes had a medium workability ranging between 50 cm and 100 cm, as shown in Figure 8. These changes in the workability range maybe attributed to various factors such as the size and shape of the beads, their distribution in the mix, and the density and viscosity of the concrete at the specified ranges, which directly or indirectly affect the workability of concrete.

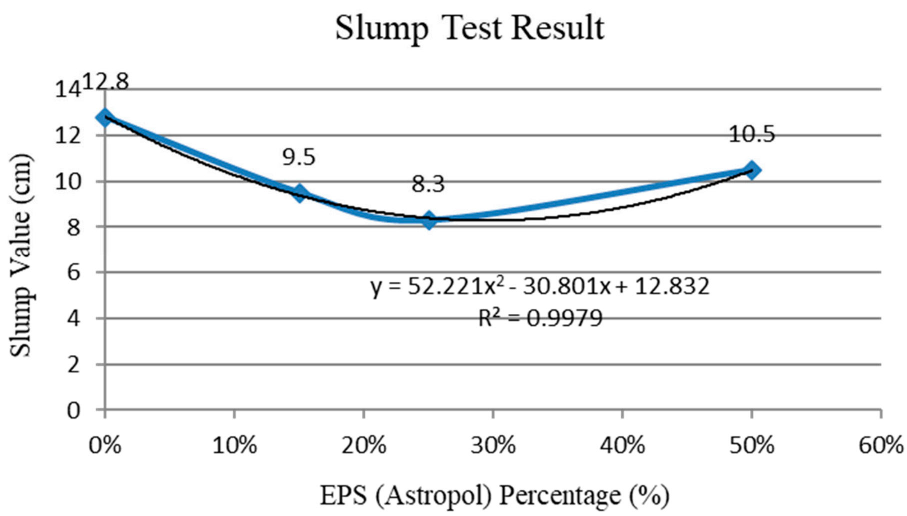

Figure 8. Slump test results.

3.3. Density of Concrete Specimens Pre- and Post-Firing

The density of the specimens pre- and post-firing was measured. It can be seen from Figure 9 that the density of the normal specimens was reduced when the addition of EPS (Astropol) increased since the density of EPS is very low and the range of the reduction is not vast, as can be seen, since not only Styrofoam but also deep-sea sand was used with EPS, which is why although a gradual reduction can be seen even up to 50%, lightweight concrete is not obtained. The densities are 2657.8 kg/m^3, 2646.1 kg/m^3, 2643.63 kg/m^3, and 2630.57 kg/m^3 for 0%, 15%, 25%, and 50%, respectively.

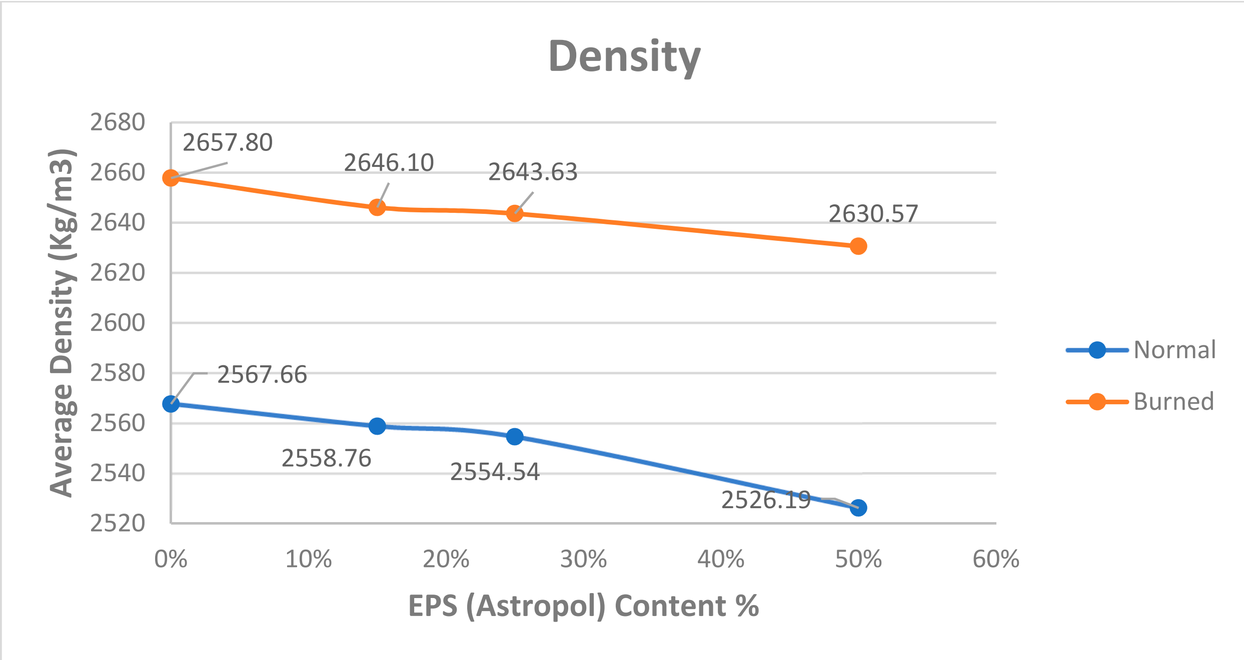

Figure 9. The density of concrete specimens before and after burning.

As for the normal specimens, a gradual reduction can also be seen in the burned specimens. Due to the fire, the combustible materials inside the concrete specimens burned and decreased the mass of the specimens; this is the main reason for why the densities were reduced. The results of the burned specimens were due to the fire losses of 3.392%, 3.3%, 3.369%, and 3.968% of the normal densities for 0%, 15%, 25%, and 50%, respectively.

3.4. Compressive Strength

To study and determine the effect of replacing the fine aggregate with the EPS (Astropol) on the compressive strength of concrete specimens in normal conditions and after burning the specimens gradually at an elevated temperature, a test was performed on the specimens as per ASTM C39 [34].

Figure 10 shows the compressive strength results, which are reduced by the replacement of fine aggregate with EPS (Astropol) compared to the conventional concrete specimens. The compressive strengths were 19.94 MPa, 19.295 MPa, 16.806 MPa, and 17.66 MPa for 0%, 15%, 25%, and 50%, respectively. The reduction in the compressive strength generally is attributed to the lower density of EPS and a weaker bond between the beads and the cement paste.

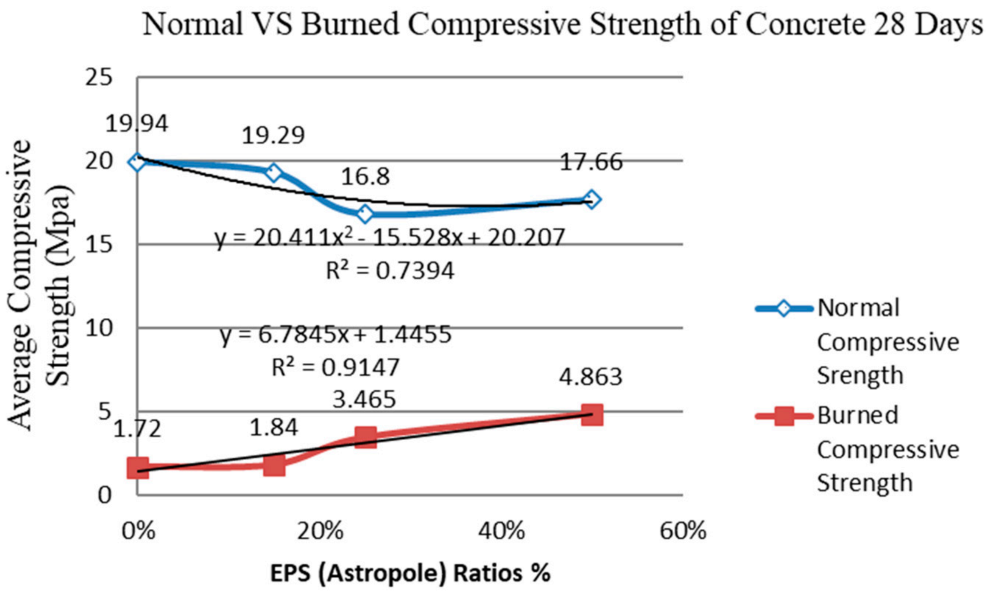

Figure 10. Compressive strength of the specimens at 28 days.

The compressive strength of a 15% replacement is the highest compared to the other ratios. Additionally, it can be seen that the compressive of a 50% replacement is greater than the compressive strength of a 25% replacement because the sand layer of EPS (Astropol) worked as a binder and increased the compressive strength of the specimens compared to a 25% replacement; however, this still remains smaller than the 15% replacement.

Figure 9 shows the post-fire compressive strength which gradually increased with the increasing ratio of the EPS: 1.713 MPa, 1.837 MPa, 3.465 MPa, and 4.863 MPa for 0%, 15%, 25%, and 50%, respectively. The 50% replacement had the highest compressive strength among all the other mixes. This increment is attributed to the addition of sea sand and the EPS, which have created a medium where even after burning is bonding still available between the composting materials. Moreover, a correlation can be seen in between the results of the compressive strength and density of the specimens at the three different EPS replacement ratios for unburnt specimens.

3.5. Splitting Tensile Strength

For splitting the tensile strength, the data before the burning process are only available since the specimens that were stored for the splitting test were specimens which were totally damaged; it could then visually assess them as having zero splitting strength.

Figure 11 displayed the burned specimens after conducting the compressive and splitting tensile test.

Figure 12 shows the test result, which can be used in ratios as 0%, 15%, 25%, and 50% for the split tensile test before the burning process achieved 3.31 MPa, 3.02 MPa, 3.17 MPa, and 3.31 MPa. The splitting tensile strength of the specimens after adding EPS (Astropol) in amounts of 15% and 25% was reduced, but at 50%, the split tensile strength was at the strength of conventional concrete. The point which should be taken into consideration is that the split tensile strengths of all the specimens are very close to each other at different ratios of EPS. This can be also attributed to the availability of a weak bond between the beads and the cement paste.

Figure 11. Specimens view after the burning processes.

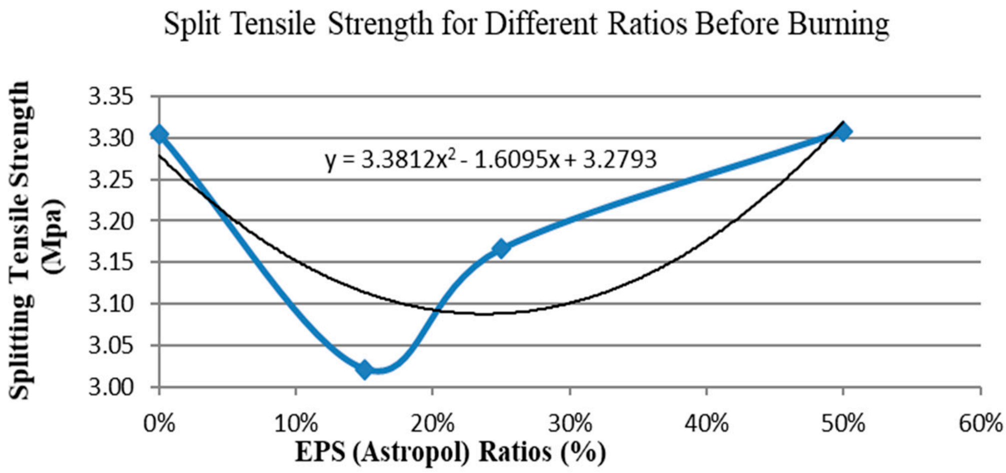

Figure 12. Split tensile strength at 28 days.

The addition of EPS beads increases the porosity of the concrete, which allows for a better distribution of stress and strain during loading. This results in a more uniform distribution of forces and reduces the likelihood of cracks forming. The EPS beads are also lightweight, which reduces the overall weight of the concrete mix. This can result in a reduction in internal stresses and strains, leading to improved split tensile strength. The addition of EPS beads can also improve the workability of the concrete mix, which made it easier to handle and place. These additional beads result in obtaining a more consistent distribution of forces during loading, leading to an improved split tensile strength. Overall, these factors may contribute to an improvement in split tensile strength when adding more EPS expanded polystyrene beads to concrete mixes.

4. Conclusions

In order to investigate the effect of replacing EPS waste (Astropol) with fine aggregate in a concrete mix, 36 cylindrical specimens from different concrete mixes were prepared; each different proportion included 8 out of 36 specimens. Then, out of 36 specimens, 20 specimens were tested in normal conditions, while the other 16 specimens were burned and tested to determine their post-fire mechanical properties.

- The compaction factor decreases gradually as the ratio of the EPS increases; however, at a 50% ratio, the trend reverses and the value increases again rapidly.
- The slump value was reduced by increasing the ratio. At 15% and 25% replacements, the slump reduced from a high workability to medium workability compared to the conventional concrete mix. However, in the 50% replacement, the slump remained in the high workability range.
- The density of all the different mix specimens in both normal and burned conditions gradually decreased as the ratio of EPS increased.
- There was a gradual decrease in compressive strength before burning the specimens at different ratios when compared to the control specimens. However, after burning the specimens, a gradual increasing trend was seen in the compressive strength values, which is why it can be said that adding EPS (Astropol) increases the post-fire mechanical property of concrete.
- Regarding the splitting tensile strength of concrete, specimens after the burning process were damaged, and it was concluded that after burning for one hour, the specimens could not sustain any tensile strength; however, for the specimens at normal conditions and different ratios, there was a very slight difference in their splitting tensile values, which were 3.31 MPa, 3.02 MPa, 3.17 MPa, and 3.31 MPa for 0%, 15%, 25%, and 50% ratios, respectively.

From the outcome of the results, the authors recommend increasing the number of tests and checking the post-fire behavior at several intervals within different temperatures and using different ratios of EPS with some chemical admixtures. This can reverse the action of fire on the concrete. The authors recommend the use of a special admixture in the concrete which can increase the capacity of the EPS material to resist fire; therefore, the adverse effect of fire can be minimized.

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