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INVESTIGATION OF THE USE OF POLYSTYRENE PLASTIC WASTE AS COARSE AGGREGATES IN CONCRETE

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ABSTRACT: Concrete is the most widely used construction material in the world, but its production consumes a large amount of natural resources and generates significant carbon emissions. In recent years, there has been growing interest in using waste materials and recycled products in concrete production to reduce its environmental impact. This study investigates the use of polystyrene plastic as a replacement for gravel in concrete. The research question addressed in this study is whether the use of polystyrene plastic in concrete can be an alternative substitute to gravel. It is also questioned if the use of polystyrene plastic in concrete can have the same properties as conventional concrete and thus be able to be used for structural purposes. The study employed a mixed design methodology to prepare three different concrete mixtures: conventional concrete, polystyrene concrete, and coated polystyrene concrete. The main findings of this study indicated that the full replacement of gravel with polystyrene plastic reached the minimum compressive strength required for structural use. The study also showed that the use of polystyrene plastic in concrete can reduce its overall weight and improve its workability. The significance of this research lies in its potential to reduce the environmental impact of concrete production by using recycled plastic waste as a replacement for natural resources. This study provides valuable insights into the use of polystyrene plastic in concrete, which can inform the development of more sustainable construction practices in the future.

Keywords: Polystyrene, Replacement, Plastic waste, Concrete, Waste utilization

1. INTRODUCTION

In the 21st century, there has been a substantial increase in plastic garbage, which has become a problem. Scientists estimated that humans produced over 8300 million metric tons (Mt) of virgin plastics in 2017, with about 6300 Mt of plastic trash produced as of 2015. Only about 9% of this garbage had been recycled. The majority of plastic products typically end up in landfills or the ocean after being used. Plastic items may take 100 to 1000 years to degrade, and there is a decreasing number of landfills that can accommodate waste. With that, this global problem should be stopped from getting worse [1].

In recent years, there has been growing interest in using waste materials and recycled products in concrete production to reduce its environmental impact [2-6], and polystyrene is one of them. Polystyrene (PS) is a synthetic polymer made from monomers of the aromatic hydrocarbon styrene [7]. PS contains an expansion gas known as pentane dissolved within the polystyrene bead. When the polystyrene bead is exposed to heat, the small amount of gas would expand which would form closed cells of Expanded Polystyrene (EPS).

Plastic is a non-biodegradable product that stays in the ecosystem for many decades. Therefore, different solutions in the field of civil engineering have been developed to mitigate this plastic problem. Plastic has been applied in different engineering structures by making it a substitute for construction materials [2-4]. With this, the quantity of different materials used in construction can be reduced. Other than that, more solutions to solving the plastic waste problems evolved where plastics can be an alternative in the construction industry.

This paper is heavily influenced by the studies of Nursyamsi [8] and Purnomo, Pamundji, & Satim [9]. Both journals are written in Indonesia and study the compressive strength of concrete that uses plastic waste as an alternative coarse aggregate. It is important to note that according to the ACI 318 Standard, Section 5.1.1, the minimum specified compressive strength of structural concrete is 2500 psi or 17.23 MPa.

The study of Nursyamsi [8] used PET plastic waste as an alternative to the coarse aggregate of concrete. The methodology used in creating the plastic coarse aggregate in this study replicates the size and shape of natural coarse aggregate used in creating concrete. The fineness modulus of the coarse aggregate that achieved the maximum compressive strength is FM 7 with 16.57 MPa.

On the other hand, Purnomo et al.'s study in 2017 [9] used polypropylene (PP) plastic waste as coarse aggregate. The coarse aggregate was molded into a plastic cube of 10 mm in thickness, 20 mm in length, and 20 mm in width. The study underwent two types of plastic specimens: where the coated plastic specimen was mixed with sand, and the uncoated plastic specimen remained as is. The results showed that the coated plastic specimen had a better bonding than the uncoated plastic specimen, as it revealed fewer cracks between the aggregate and mortar. The fineness modulus of the coarse aggregate was 4.45. The uncoated plastic achieved 14.25 MPa, while the coated plastic aggregate achieved 17.5 MPa, which was the minimum required compressive strength for structural concrete.

Plastic aggregates used as fine or coarse aggregates have a disadvantage in their mechanical properties when compared to natural aggregates. These are caused by a low bond strength between the surface of the plastic aggregate and the cement paste, and as plastic is a hydrophobic material, it limits the water movement within the mixture [10]. However, improving the characteristics of the surface of plastic aggregates by amplifying the hardness and texture would enhance the mechanical properties of plastic aggregate with mortar [11].

Furthermore, the use of sand coating on the Polystyrene coarse aggregates would provide more surface area for water and cement to bind with, as plastics are known to be hydrophobic, while ordinary sand is known to be hydrophilic. Sand coating would provide better workability with the concrete mix and create durable concrete.

2. RESEARCH SIGNIFICANCE

The significance of the study is to encourage construction industries to use an alternative material for gravel, such as plastic, which would help reduce the ongoing plastic problem in the Philippines. This can help reduce pollution, lessen flooding in communities, and improve the quality of the environment, making a better future for the world. Other than that, it can also aid other civil engineering-related research that aims to help the environment by reducing the global plastic problem. With this, the study lies in its potential to tackle two pressing global challenges: plastic waste management and resource depletion in the construction industry. By replacing gravel with plastic waste, substantial amounts of plastic waste can be diverted from landfills and oceans, thereby reducing its adverse effects on ecosystems and human health. With this replacement, it would reduce the need for gravel extraction, a process that often leads to habitat destruction, soil erosion, and water pollution. By having an alternative approach, the study aims to encourage sustainable consumption and procurement practices within the construction industry, contributing directly to SDG 12: Responsible Consumption and Production.

3. METHODOLOGY

The methodology employed in this study involved the procurement and utilization of two distinct types of Polystyrene coarse aggregate, namely uncoated Polystyrene, and sand-coated Polystyrene. The plastic aggregates were sourced from a reliable supplier specializing in Polystyrene plastic materials. The procurement process ensured the acquisition of clean, high-quality plastic aggregate conforming to the required specifications.

3.1 Materials

The materials used for the study consisted of Ordinary Portland Cement Type 1P, expanded polystyrene coarse aggregates (EPCA), ordinary coarse sand, and water, which are the main materials used to create the concrete mix. The concrete samples underwent slump test and compressive strength test, as these are the common tests used to determine if the concrete mix design would achieve the desired slump and if the samples would pass the minimum required compressive strength for concrete.

For the slump test, the materials needed were the slump cone, base, tamping rod, scoop, funnel, measuring tape, and cleaning brush. On the other hand, a cylindrical mold and universal testing machine are needed for the compressive strength test.

3.2 Plastic Coarse Aggregates

In order to obtain the required EPCA, the researchers contacted Pakvite Manufacturing Corporation to aid in manufacturing. Pakvite Manufacturing Corporation manufactures food container products that are made from Styrofoam. Styrofoam is made up of Polystyrene, Calcium stearate, and Talc. Calcium stearate and Talc are used as a thickening agent and lubricant, as Styrofoam containers are seen to be glossy and smooth. The materials were placed in an extruder, where a polymer material combined with additives was melted and formed into a roll. As the products were produced, there were Styrofoam scraps, which were considered to be the company’s waste and were subjected to recycling. The Styrofoam scrap was shredded and placed into an extruder, which produced a long, thin, solid, and cylindrical shape. Afterward, the plastic was submerged in water to cool down. Then, the plastic rods were solidified into a mass with a thickness of 20 mm, as seen in Fig. 1.

Fig.1 Hardened Molded Polystyrene.

The mass was then crushed to the desired size that would pass the 20 mm sieve, as shown in Fig. 2.

Fig.2 Crushing Polystyrene.

3.3 Coated Polystyrene Coarse Aggregate

In order to produce the coated Polystyrene aggregates, the process began by gathering a sufficient amount of coarse sand, which served as the base material for the coating. The coarse sand was obtained from a local hardware construction store.

A heat source, such as a burner or a furnace, was utilized to prepare the hot sand. The sand was placed in a container that was exposed to the heat source, allowing it to gradually increase in temperature. The heating process also involved stirring or turning the sand intermittently to ensure an even distribution of heat. While the sand does not require precise temperature control, it should reach a sufficiently high temperature to facilitate the coating process.

Next, the Polystyrene Coarse Aggregates were prepared separately. Once the hot sand and Polystyrene coarse aggregates were prepared, the mixing process took place. The Polystyrene coarse aggregates were transferred to the burner and carefully mixed until the plastic particles were uniformly distributed and coated with the hot sand. This ensured a homogenous blend of the material, resulting in a composite mixture with improved properties.

During the mixing process, the heat from the sand softened the plastic aggregate, enabling them to adhere to the sand particles. The result was a coated mixture where the plastic aggregate became firmly attached to the sand, creating a cohesive composite material.

3.4 Natural Coarse Aggregate and Coarse Sand

The gravel and coarse sand were obtained from KBon Construction Supply, which is located in Quezon City, Philippines. The physical properties of gravel and coarse sand, such as specific gravity, absorption, and moisture content, were obtained using ASTM C127 (Specific Gravity and Absorption), while dry rodded density was obtained using ASTM C29 (Dry rodded density), and fineness modulus was obtained using ASTM C33 (Fineness modulus of Aggregates).

3.5 Mix Design and Tests

For the concrete mix design, the ACI mix design was followed for the computation. Three mix designs were prepared, as shown in Table 1, where different coarse aggregates were used, namely the sand-coated PS plastic coarse aggregate, PS plastic coarse aggregate, and the conventional coarse aggregate. The researchers were able to produce three mix designs for each coarse aggregate used for the study. Since the two mixed designs have a similar coarse aggregate content, the mixed design that contains the coated polystyrene aggregate requires more water, as there is more sand in total compared to the uncoated polystyrene aggregate.

Table. 1 Mixed Design per 1m3 of concrete.

Type	w/c	Ce (kg)	F (kg)	C (kg)	W (kg)
Sand Coated PS Plastic	0.76	297.1	843.23	346.1	226
PS Plastic	0.75	297.1	843.23	346.1	223
Conventional Concrete	0.81	302.1	811.45	1004	245

At least five specimens were prepared for sand-coated PS plastic coarse aggregate, PS plastic coarse aggregate, and the conventional coarse aggregate. Slump test was carried out using the ASTM C143 after the mixing process. Then, a compressive test was performed after the 28-day curing period in accordance with ASTM C39.

4. RESULTS AND DISCUSSION

Compressive tests were performed on the 28-day-aged concrete cylindrical specimens with a diameter of 10 cm and a height of 20 cm. The results of the compressive strength tests are shown in Tables 2, 3, and 4.

Table 2. Compressive Strength of Concrete Specimen with Conventional Gravel.

CC	Load (kN)	Strength (MPa)	Weight (g)	Time (s)
1	168.18	20.99	3844.5	18.6
2	134.42	16.78	3806.9	17.3
3	159.39	19.89	3897.5	17.7
4	157.47	19.66	3803.8	10.5
5	162.77	20.32	3933.0	14.0
Average	156.45	19.53	3857.14	15.62

Note: CC – concrete specimen.

Table 3. Compressive Strength of Concrete Specimen with Polystyrene Aggregate (PA).

CC	Load (kN)	Strength (MPa)	Weight (g)	Time (s)
1	98.37	12.28	2729.2	13.5
2	103.19	12.88	2757.3	10.9
3	107.67	13.44	2851.2	13.7
4	80.33	10.03	2686.1	11.4
5	82.91	10.35	2723.3	14.2
6	106.31	13.27	2825.5	13.4
Average	96.46	12.04	2762.1	12.85

Note: CC – concrete specimen.

Table 4. Compressive Strength of Concrete Specimen with Coated Polystyrene Aggregate (PSA).

CC	Load (kN)	Strength (MPa)	Weight (g)	Time (s)
1	153.62	19.17	2949.9	13.4
2	167.55	20.91	2966.2	18.4
3	131.70	16.44	2866.0	12.7
4	136.32	17.01	2958.0	13.4
5	156.50	19.53	2910.3	12.6
6	154.29	19.26	2953.3	15.5
Average	150.00	18.72	2933.95	14.33

Note: CC – concrete specimen.

4.1 Slump Test

The results of the slump test showed slumps of around 90 mm to 100 mm for the conventional, plastic, and sand coated plastic aggregate. The results suggest that the concrete mixture can be used for structural purposes. At first, there were problems encountered in the mix design because the results did not reach the desired slump. This was then adjusted by reducing or increasing the mixing water content by 2 kg/m^3 of concrete for each increase or decrease of 10 mm to get the desired slump.

4.2 Physical Appearance of Concrete Specimens

In a study on the compression strength of concrete cylinders, it was found that a significant increase in compressive strength was observed when the fiber content was increased. The increase can be caused by the porosity reduction [12]. Other than that, it can be seen that the cylinders are of the right shape, meaning that there is no leakage present while they cure in the mold. Leakage can disrupt the compression strength of the specimens since a constant area is needed.

4.3 Compressive Strength of Specimens

After subjecting the specimens to compressive strength test, it was observed that the concrete specimens that contained uncoated polystyrene coarse aggregate showed weak bonding between the uncoated polystyrene aggregate and mortar. This result is caused by the low hydraulic conductivity of polystyrene, meaning that it does not allow fluid to move easily since the polystyrene used has no pore spaces and does not fracture easily. Another reason would be the hydrophobic characteristics and smooth surface of the uncoated plastic aggregate. Examples of this are shown in Fig. 3.

Fig.3 Rupture of concrete specimen containing uncoated polystyrene aggregates.

The highest compressive strength achieved was 12.88 MPa, which is below the building minimum structural compressive strength of 17.23 MPa, as stated in the ACI 318 Standard. With these results, it confirms a low compressive strength of concrete containing uncoated plastic coarse aggregates.

To enhance the mechanical properties of the plastic aggregate with the mortar, the methodology of Choi, Moon, Chung, & Cho [11] was used to coat the plastic polystyrene coarse aggregate with sand. It showed a significant increase in the absorption from 0% to 1.47%. With this, the concrete specimens containing coated polystyrene coarse aggregate showed similar results to concrete specimens containing conventional gravel, achieving average compressive strength of 18.72 MPa and 19.53 MPa, respectively. The coated polystyrene coarse aggregate shows high bonding with the mortar as illustrated in Fig. 4. It was also observed that the increase of compressive strength and less crack appearance proved a high bonding. The highest compressive strength achieved was 20.91 MPa, which reached the building minimum structural compressive strength of 17.23 MPa. Therefore, with the results, the concrete containing coated polystyrene coarse aggregates can be used for structural purposes.

Fig.4 Rupture of concrete specimen containing coated polystyrene aggregates.

According to the ACI Committee 213 Guide for Structural Lightweight Aggregate Concrete [13], lightweight concrete can be classified according to its density, which normally ranges from 320 to 1920 kg/m^3. The calculated density of the concrete specimen containing coated polystyrene coarse aggregates was 1780.36 kg/m^3, which is within the numerical range of what is considered to be a lightweight concrete. Furthermore, it can be seen in Fig. 5 that the load that the PSA can withstand is close to the results of conventional concrete. The load that conventional concrete can withstand ranges from 134.42 kN to 168.14 kN, while the load that PSA can withstand ranges from 131.70 kN to 163.55 kN. This signifies that the PSA concrete can also be used for structural purposes. However, the same does not apply with the PA specimens since its load capacity only ranges from 80.33 kN to 107.67 kN.

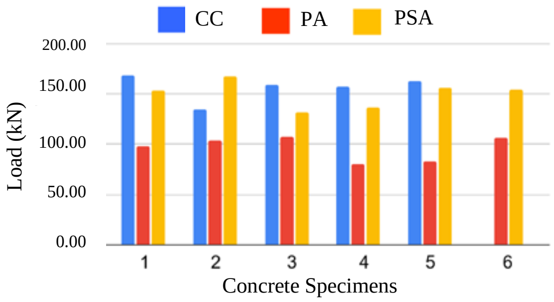

Fig.5 Load per Concrete Specimen.

The average compressive strength and the water-cement (W/C) ratio are shown in Fig. 6. It can be seen that as the compressive strength increased with higher W/C ratio. higher percentage of water in the mix design was used in the PSA specimens since the aggregates used were covered in sand which explains the higher W/C ratio obtained.

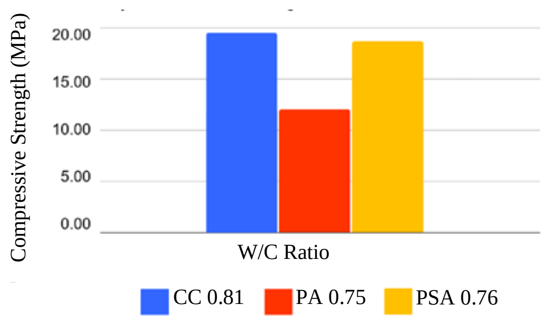

Fig.6 Compressive Strength vs W/C Ratio.

4.4 Stress-Strain Curve and Load Displacement of Concrete Specimens

The purpose of a stress–strain curve is to provide a graphical representation of the relationship between the stress and strain of a material. The values are usually obtained from a tensile stress test, but as per the limitations of this study, the values were obtained using the compressive stress test.

The load and displacement values were obtained from a displacement transducer, which is an electromechanical device used to convert vibrations into electrical current, and to compile the data into a Microsoft Excel file. The strain value was obtained by dividing displacement over the original length of the specimen, while stress was obtained by dividing load over the cross-sectional area of the specimen. Due to budget limitations, only three samples were considered in obtaining the stress-strain curve of each group. The stress-strain curve of PA specimens is shown in Fig. 7. It can be seen that the strain for the PA specimen reaches higher values compared to the strain of the PSA specimen. This is due to the higher compressive strength of the PSA specimen. An increase in the compressive strength of the specimen gives a lower displacement value, thus giving a lower strain value.

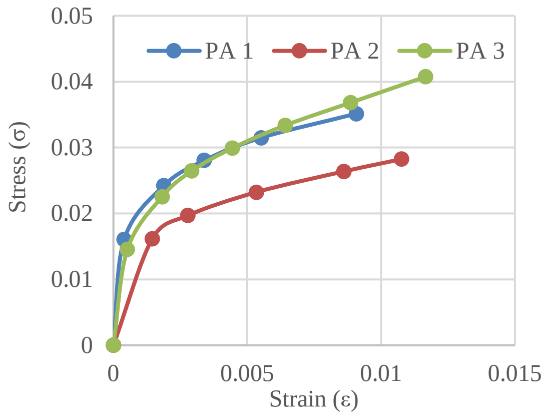

Fig.7 Stress-Strain Curve of PA.

In the PSA stress-strain curve is shown in Fig. 8. It also resembles a typical stress-strain curve. Although in this curve, the line reaching the yield strength of the concrete is much steeper than of the PA stress-strain curve. This shows that the PSA concrete is less brittle compared to the PA concrete.

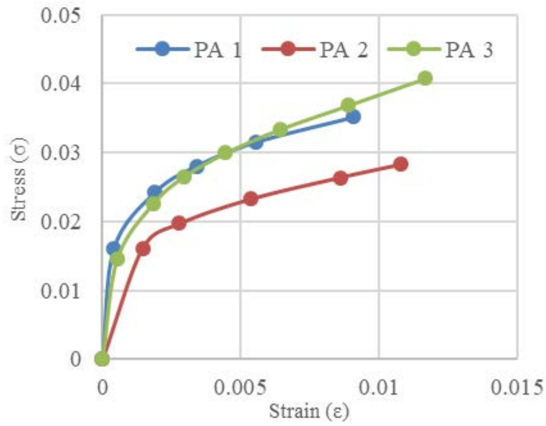

Fig.8 Stress-Strain Curve of PSA.

According to a study by Zhang and Gjvorv [14], the modulus of elasticity is dependent on the compressive strength of concrete, properties of coarse aggregates, the proportion of the aggregates in the concrete, the quality of cement paste, and additional mineral admixtures. Specifically focusing on the W/C ratio, this crucial factor plays a significant role in determining the properties of concrete, including its modulus of elasticity.

As the W/C ratio increases, the strength to resist deformation decreases proportionally. It can be observed in Table 5 that this study follows the findings of Shelorkar [15]. However, for the PA specimens, it was unable to follow due to low bonding strength and low compressive strength. The modulus of elasticity was obtained from the respective graphs of the stress-strain curve.

It can also be seen that the PA has the lowest modulus of elasticity compared to the other specimens. With this, it can be said that PA is the most brittle among the other specimens. While PSA shows the highest modulus of elasticity which shows that it is the least brittle. This can also be seen in Fig. 7 and Fig. 8 where the elastic region of PSA is steeper compared to PA.

4.5 Concrete Strength Applications

The average compressive strength of conventional concrete, PA, and PSA were determined to be 19.53 MPa, 12.04 MPa, and 18.72 MPa, respectively. Given the compressive strength of conventional concrete and PSA, the type of concrete construction which it can be used are basement and foundation walls and slabs, walks, patios, and steps and stairs. While for the PA compressive strength, even if the results did not reach the desired strength value, it can still be used in concrete fills [16].

5. CONCLUSIONS

The results of the compression testing of the concrete specimens showed that the concrete specimen containing coated plastic coarse aggregate reached the minimum compressive strength required for structural use. The enhancement of sand coating of the polystyrene surface also increased the bond between the coarse aggregate and mortar.

Based on the experimental results of this study, it can be said that fully replacing gravel with sand coated polystyrene coarse aggregate in concrete can be used for structural purposes and is also considered to be a lightweight concrete.

6. RECOMMENDATIONS

Based on the findings and conclusion of this research study, several key recommendations can be made to address the research problem and increase the accuracy of the results. These recommendations are aimed at bridging the identified gaps and improving the current practices in using recycled polystyrene as a replacement for gravel.

In particular, the following are recommended:

1. It is recommended to explore alternative methods for crushing the hardened molded polystyrene. The current method of crushing polystyrene has demonstrated certain limitations in terms of safety and inefficiency.
2. The researchers recommend testing the compressive strength on the 7th, 14th, and 21st days to determine the compressive strength of concrete as it cures.
3. Due to insufficient time and lack of equipment, the researchers were not able to test the fire resistance of the cylindrical concrete that underwent compressive testing to check if the plastic would melt and serve as a plastic filling on the cracks.
4. It is recommended to have different varieties of partial replacement of polystyrene to gravel to check if its compressive strength with given partial replacement would yield better results than having a full replacement of gravel with polystyrene.
5. The experiment is only limited in determining the compressive strength of fully replaced gravel with polystyrene. The researchers would like to recommend doing tensile testing on the concrete.
6. Lastly, the researchers would recommend the use of a variety types of polymer and not only limit future researchers on the use of recycled polystyrene.

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