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Plastic Coarse Aggregates with Low- and High-Density Polyethylene with Improved Shore Durometer Hardness as Partial Replacement to Natural Coarse Aggregates

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Abstract. One of the issues in engineering field is the massive demand of natural aggregates in building, which in some areas causes shortages in supplies. While globally, increasing production and consumption of plastic, which takes decades to decompose, is among the main issues that humanity is now experiencing as the world progresses. In this study, plastics with improved Shore Durometer hardness was looked into as a partial substitution for natural coarse aggregates (NCA) in solving these problems. The LDPE/HDPE plastic coarse aggregates were developed using the best ratio of LDPE and HDPE plastics by melting, molding, and forming into 5mm, 10mm, and 15mm cubes. The gravel substitution volumetric were 2.5%, 5.0%, 7.5%, and 10.0% of the concrete mixture, respectively. When the density of concrete, compression, flexure, and split tensile strength of concrete were examined, a 5% replacement with 10mm size produced the best results. A lighter-weight concrete is evident between the controlled sample and the experimental sample when the best size configuration and percentage replacement leading to a 2.97% difference. In general, the compressive strength and flexural strength of (plastic coarse aggregate) PCA-based specimen is 20.23% and 3.78% higher than that of the controlled specimen, respectively. However, it was found that the split-tensile was lower than the controlled specimen by 2.72%.

1 Introduction

Nowadays, the majority of the construction supplies used in civil engineering field originates from natural sources like coarse aggregates. The global economic development demands are rapidly depleting global material resources [1]. Because of the expanding need for essential buildings, bridges, roads, etc., gravel mining have widened to help with the world's development. Apart from its immense importance to the economy of many nations, the construction industry also significantly affects the environment by causing a massive depletion of natural resources. As concrete mixture requires a lot of cement, sand, and gravel,

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the way concrete is currently practiced is deemed unsustainable [2], [3]. The lack of resources for construction materials is causing discord and contributing to the low GDP issues that many countries are facing [4]. One example of this is the city of Rio Branco in the Brazilian Amazon region which is experiencing increase in cost of natural aggregates as they depend on intricated logistical activities to ensure their supplies because aggregate resources are scarce in their area [5]. In some, the lack of natural aggregate causes debris from construction and demolition to be incorporated into structural concrete [6]. Thus, recycling waste by applying it to make construction materials, especially in concrete, is a technique that addresses material efficiency [1]. Due to the global trend towards green construction, the use of recovered plastic waste has drawn increased attention [7]. Many researchers have discovered effective methods for recycling and reusing waste matters utilized in concrete to make gravel or coarse aggregates sustainable [8]. In a study of S. İpek, et al. [9], it is stated that concrete production might become environmentally friendly if plastics are used as aggregates in construction.

Globally, the environment was recognized to be threatened by plastic garbage since it may take a billion years for it to gradually disintegrate [10]. Plastic is produced and used extensively around the world for a variety of purposes, including food packaging, bottles, straws, bags, and wraps. Packaging is the global industry with the most plastic use, followed by the building industry [11]. Throughout the time, those made of plastic were referred to as "single-use products", which means they were intended to be discarded after only one usage [12]. As manufacturing expands, an enormous quantity of plastics must be disposed as the trend toward urbanization increases the creation of solid trash [13]. Due to the recent Coronavirus outbreak, single-use plastic usage has increased in homes across the world [14]. Aside from single used plastics, another threat to the environment are the microplastics, which are well recognized to harm the terrestrial, marine, and atmospheric environments, is one type of defined marine litter [15]. When compared to sand, these microplastics may be easily moved by the wind and can penetrate the soil's gravel and sand layer and infiltrate aquifers deep underground [16], [17]. Wastewater is one source of microplastics, wastewater may contain polymers like polypropylene and polyethylene [18]. To minimize and recycle plastics, developing an environmentally friendly alternative or innovations are required [19].

Some studies have used plastics as partial replacement to coarse aggregates however the shape and size is differed from this study. In the study of S. İpek,et al., H. Abdelmoti et al., and A. J. S. Dolores et al. [9], [20], [21], the concrete with plastic pellets have shown decrease in compression and split tensile strength for both 7 days and 28 days curing. One factor that has been stated for this is due to weak bond between cement and plastic pellets. The weak bond between these materials was due to weak interfacial transition zone because of the shape of the pellets [22]. It is identified that concrete's plastic viscosity is most influenced by coarse aggregate's flatness, compressive strength of concrete is most influenced by coarse aggregate's angularity, and concrete flexural strength is most influenced by coarse aggregate's roughness [23]. Because of the cube—shape with rough surface PCA that were used in this study, it has been observed that it provided a better bond between the cement paste and the PCA itself. Others also used plastic powder but due to microplastic hazard to human and the environment, this is not recommended. The route of entrance of microplastics might be by skin contact, inhalation, or ingestion [24] if this plastic powder will be utilized in construction industry. A study of M. O. Rodrigues et al. [25], stated that microplastics may have detrimental impacts on development and reproduction, as well as immunological and stress responses of human.

This study used two different types of abundant polyethylene plastics: LDPE and HDPE. The World Bank Group (WBG) study from the year 2021 states that as of the year 2019, an average of only 28% of plastic have been collected for recycling. From all the other type of plastics, LDPE is the most widely utilized plastic substance available [26]. From the study of the WBG, in year 2019 an average of 10% of LDPE were collected for recycling and the rest were left as waste. Because it is adaptable and waterproof, LDPE is a form of plastic which is frequently utilized [27]. Another type of polyethylene that is popularly used is the HDPE which has an average of 20% higher recycling rate compared to LDPE. These HDPE plastics are typically tough plastics that are frequently employed in a variety of industrial applications, including bottles, dinnerware, and the like [28]. These types of plastic are known to be difficult to naturally breakdown providing a very slow degradation process.

In addition, this study aimed to improve the shore-D hardness of combined plastics before incorporating to concrete. This factor was seen to help in the improvement of the mechanical properties of concrete specially the compressive strength, as this mechanical property tends to decrease with the addition of plastics to concrete as sited from other studies. After testing the PCA-based concrete under different mechanical properties, this study aimed to determine best size configuration and percentage substitution of PCA to concrete.

2 Materials and Methods

In this study, two experimental phases have been conducted. First is the improvement of the Shore Durometer Hardness property of the developed PCA with the blend of LDPE and HDPE plastics. Shore Durometer Hardness properties of PCAs were enhanced to overcome the discrepancy between the hardness properties of NCA and PCA. Given that LDPE is the most prevalent kind of plastic trash and has a lower rate of recycling than HDPE, it ends up making up a bigger proportion of the final PCA blend. The ratios that were used in combining the two said plastics are: 100 to 0, 90 to 10, 80 to 20, and 70 to 30, following low-density to high-density polyethylene (LDPE:HDPE) ratio respectively. Both materials were subjected to melting and then cut into various-sized cubes. It has been observed from the study of E. AKDOĞAN et al. [29] the density, hardness, and tear strength values increased when HDPE was added to LDPE polymer. After combining the two plastics, each blend undergone ASTM Standard of D2240 [30], also known as the Standard Method for Durometer Hardness. The optimal ratio of low-density polyethylene and high-density polyethylene blend that gave the highest Shore Durometer Hardness proceeds to the next phase.

The second phase of this study aims to incorporate the best ratio of low-density polyethylene and high-density polyethylene with the highest Shore Durometer Hardness in a concrete mixture following the 1:1:2 concrete mix proportion. The density of the materials that were used for the concrete mixture were tested and determined under ASTM standards and water displacement method. In determining the optimum dimension and percentage replacement of PCA with low-density and high-density polyethylene blend, the concrete was cured for 14-days and tested under different mechanical properties. The different size configuration for the PCAs were 5mm, 10mm, and 15mm cubes and the percentage replacement that were utilized in this study were 2.5%, 5%, 7.5%, and 10%. Only concrete with a water-to-cement ratio of 0.50 was used in design mixes so that the ratio of water to cement remains constant. As per M. A. Farediwala and M. A. Jamnu [31], when the proportions of the water-to-cement ratio and the mix proportion was maintained constant, the relation with the compressive property and workability of blended concrete will be linear. The concrete specimens that were tested were size 4 inches in diameter and 8 inches in height for density, compression, and split tensile test. For flexural testing, the rectangular specimen has been casted under 6 inches by 6 inches cross sectional area with 21 inches of length rectangular molds. Considering the three-size configuration and four percentage replacement for NCA, this study came up with twelve design options which were considered as the experimental samples. One controlled sample was made to determine the improvement in the properties of concrete.

The tests that were conducted to determine the mechanical properties of concrete were aligned with the standards of the American Society for Testing and Materials. The testing for the density, compression, split tensile, and flexural strength of concrete were ASTM C138 [32], ASTM C39 [33], ASTM C496 [34], and ASTM C78 [35], respectively. Universal Testing Machine was used in conducting the mentioned ASTM tests for hardened concrete. After gathering all results, in determining the optimal design option, multi-attribute decision making (MADM) models through Technique for order-preference by similarity to ideal solution (TOPSIS) analysis was used. This is among the most popular techniques for making decisions based on multiple criteria [36]. This analysis started with critique method which a survey was conducted among the numbers of civil engineer professionals to determine their priority amongst the design constraints. The optimum design option is demonstrated by the estimated Value of Preference and alternative ranking when all design constraints in the study were taken into account.

3. Results and Discussion

The melted low-density and high-density polyethylene with four different ratios were tested to determine the Shore Durometer Hardness property. Each block was tested in three different faces: left face, middle face, and right face, to see the mean value of the hardness property per blended plastic. Tabulated are the results below as shown in **Table 1**:

Table 1. Result of Shore Durometer Hardness for LDPE/HDPE Blends

Average Shore Durometer Hardness for each face	100% LDPE 0% HDPE	90% LDPE 10% HDPE	80% LDPE 20% HDPE	70% LDPE 30% HDPE
Trial 1	37.5	41.2	40.2	50.5
Trial 2	40.2	41.2	43.0	49.7
Trial 3	36.5	40.7	44.8	49.5

According to the graph below as shown in **Fig.1**, the combination of 70% LDPE and 30% HDPE, gave the greatest Shore Durometer Hardness Property. It is obvious that the blend without HDPE has the lowest hardness property among the other blends.

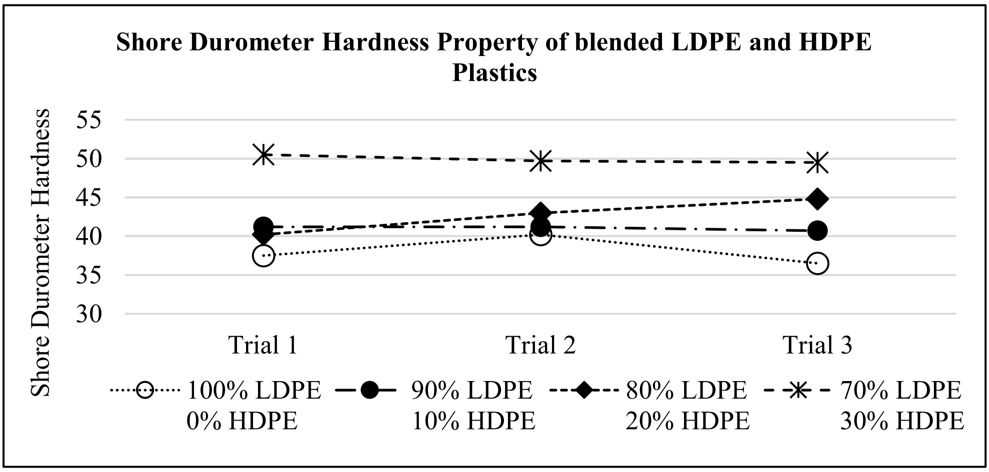

Fig.1. Shore Durometer Hardness Property of blended LDPE and HDPE Plastics

The table below (**Table 2**) shows the result of the mechanical properties of controlled specimen and all experimental specimens. Using the Universal Testing Machine (UTM), tests in accordance with the ASTM Standards were performed to all cylindrical and rectangular specimens.

Table 2. Test Results for PCA-based concrete

PCA Size	PCA % Substitution	Density (kg/m3)	Compression Strength (MPa)	Split Tensile Strength (MPa)	Flexural Strength (MPa)
Controlled Specimen		2321	17.223	2.388	2.488
5 mm	2.5%	2285	19.386	2.818	2.345
5 mm	5.0%	2266	19.299	2.721	2.263
5 mm	7.5%	2248	21.534	2.952	2.133
5 mm	10%	2206	15.495	2.651	2.330
10 mm	2.5%	2327	17.642	2.860	2.794
10 mm	5.0%	2253	21.100	2.324	2.585
10 mm	7.5%	2224	13.038	2.327	2.351
10 mm	10%	2197	12.838	2.495	2.376
15 mm	2.5%	2299	14.203	2.574	3.116
15 mm	5.0%	2252	17.496	2.560	2.559
15 mm	7.5%	2246	18.732	2.317	2.556
15 mm	10%	2234	18.109	2.133	2.357

As a result of the test, the combination with the lowest density out of all the mix designs has a PCA of 10mm size with a 10% partial replacement. In comparison to the controlled specimen, this design mixture produces 5.5% lighter concrete. The graph below, as shown in **Fig. 2**, presents the illustration of different densities attained by all design mix in kg per cubic meter:

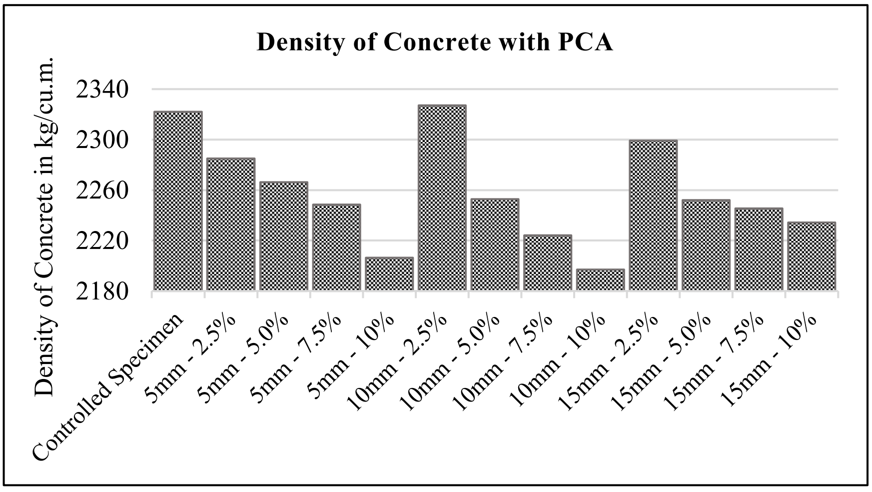

Fig.2. Density of Concrete with PCA

Design mix 5mm—7.5% had a compressive strength of 21.534Mpa, which was followed by design mix 10mm—5.0%, which had a compressive strength of 21.100Mpa. When compared to the controlled samples, these experimental samples' compression strengths increased by 22.25% and 20.24%, respectively, for 5mm—7.5% and 10mm—5.0%, respectively. The graph below, as shown in **Fig. 3**, presents the illustration of the different compressive strength attained by all design mix in Mpa:

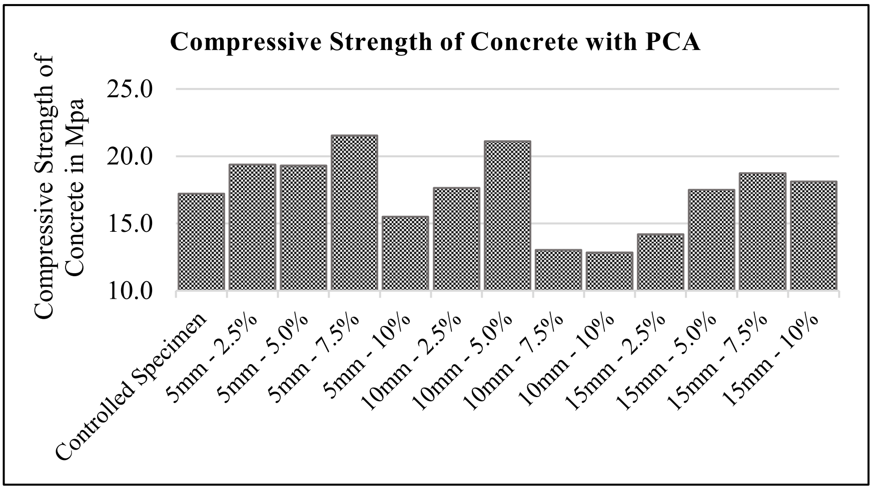

Fig.3. Compressive Strength of Concrete with PCA

In comparison to the control sample, experimental samples' split tensile strength rose by 17.99% for 10mm—5.0% and 21.12% for 5mm—7.5%. The graph below, as shown in **Fig. 4**, presents the illustration of the different split tensile strength attained by all design mix in Mpa:

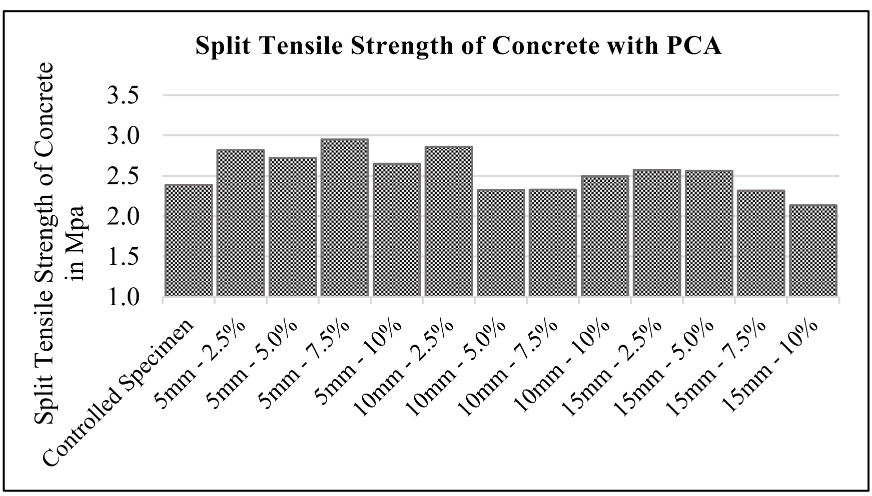

Fig.4. Split Tensile Strength of Concrete with PCA

According to the gathered data, the design mix of 15mm—2.5% PCA-based concrete has the maximum flexure strength (3.116 Mpa), followed by the design mix of 10mm—2.5%

(2.794 Mpa). These experimental samples had flexural strengths that were 22.41% and 11.59% higher with regards to the controlled samples, respectively. The graph below, as shown in **Fig. 5**, presents the illustration of the different flexural strengths attained by all design mix in Mpa:

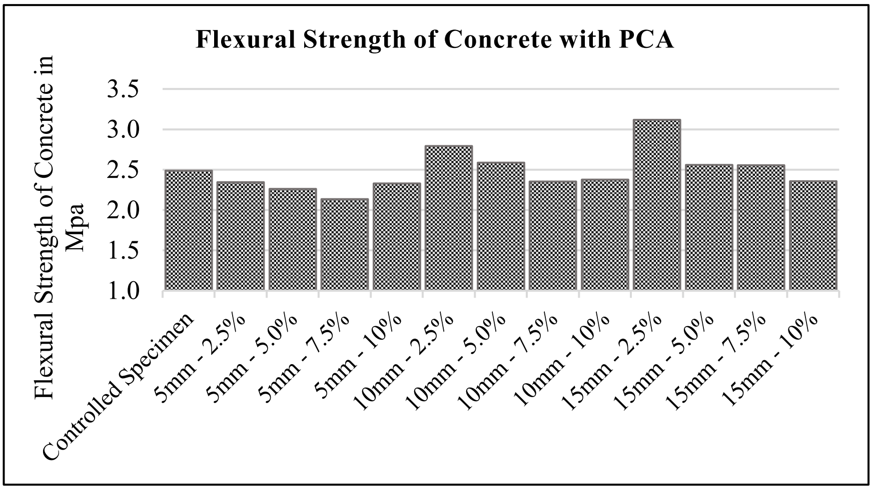

Fig.5. Flexural Strength of Concrete with PCA

After gathering the results, models in choosing the best mix from the list of options were used through TOPSIS Analysis. Using the weights for each constraint from the conducted critique method, the priority value (Pi) for each design option was calculated. In terms of significance, compressive strength took over flexural strength. The density of concrete is the one that was given the least weight between all four constraints. Considering the Pi value, the design options were ranked as follows as tabulated in **Table 3**:

Table 3. Test Results for PCA-based concrete

PCA Size	PCA % Substitution	Ranking
5 mm	2.5%	4
5 mm	5.0%	5
5 mm	7.5%	3
5 mm	10%	10
10 mm	2.5%	2
10 mm	**5.0%**	**1**
10 mm	7.5%	12
10 mm	10%	11
15 mm	2.5%	8
15 mm	5.0%	7
15 mm	7.5%	6
15 mm	10%	9

It was shown above that the highest calculated preference value belongs to design mix 10mm—5.0% followed by the 10mm—2.5% design mixture. Comparing the property of the optimal design mix to the controlled specimen, the data are shown in **Table 4** with the calculated percentage difference.

Table 4. Properties of optimal design mix and controlled specimen concrete

Concrete Property	Controlled Specimen	10mm-5.0%	$\%_{diff}$
Density (kg/m3)	2321	2253	2.97%
Compressive Strength (Mpa)	17.223	21.100	20.23%
Split Tensile Strength (Mpa)	2.388	2.324	2.72%
Flexural Strength (Mpa)	2.488	2.584	3.78%

4. Conclusion

This study has shown that both kind of plastics may be combined (LDPE and HDPE) to improve the PCA's Shore Durometer Hardness. The optimal LDPE to HDPE ratio is found in plastics that were made up of 70% LDPE and 30% HDPE. The optimal size configuration has been identified to be a 10mm cube with a 5% replacement percentage in terms of volume to the amount of NCA present in concrete. This size and percentage substitution of PCA was tested under 1:1:2 concrete mix proportion with 0.5 water-cement ratio.

By utilizing 10mm cube size of PCA with 5% partial replacement to NCA in concrete, it increased the concrete's compressive and flexural strengths by 20.23% and 3.78%, respectively. In addition, it was noted that the concrete was 2.97% lighter than the mix that did not contain PCA. On the other hand, in this design composition, a reduction of 2.72% in the split tensile capacity of concrete was seen.

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