Manufacturing and Performance Evaluation of Recycled Plastic (HDPE) Coarse Aggregates in Concrete

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**Abstract:** Recycling plastic for use in concrete is a thorough process that involves repurposing plastic pieces that have been stripped and washed through templates. Among the top contenders for concrete mixtures are sand and plastic rock dust, known for their strength. In this study, we utilize locally sourced, recycled plastic from a shredder, ranging from 1mm to 6mm in size. The plastic is then melted at a temperature between 294 and 339°C and combined with sand and rock dust. After 100% melting of the plastic bond with sand particles and rock dust particles, this mixture is poured into the water through a suitable size mesh we need, the hot particles mixed with the plastic sand and plastic rock dust when in the water will form a stronger bond. These aggregates are stronger in compression and very strong in tension than the ones we can use in concrete. Here in this paper, the secondary or backscattered electron signal is detected capturing the secondary or backscattered electron signal after projecting a concentrated electron beam through the medium, and a detailed high-resolution image of the sample particles can be obtained. The analysis of the aggregates involves scanning electron microscopy (SEM). Additionally, elemental identification and quantitative composition data are acquired through an "energy-dispersive X-ray analyzer" (EDX or EDA). The initial aggregates' size ranges from 2.36 to 20 mm, conforming to granulometry standards outlined in ASCE-C330, C33-99a, and IS 383-2019. These standards are subsequently employed for further concrete testing and the production of precast concrete components. The research explores the utilization of lightweight plastic aggregates in concrete and the incorporation of high-density plastic materials for the preparation of plastic aggregates, both in single and well-graded forms. The methodology for manufacturing plastic aggregates for civil infrastructure and the composition integrating this type of aggregate constitute the focal points of this study.

**Author keywords:** high-density polyethylene (HDPE), filler; repurposed plastic rock dust and plastic sand aggregate, scanning electron microscopy (SEM), energy-dispersive X-ray analyzer (EDX or EDA), compressive strength of concrete.

**Introduction:**

Addressing a critical concern in environmental conservation, there has been a surge in the utilization of diverse plastic-based objects[1]. Incorporating materials containing plastic waste into industrial processes stands as an eco-friendly approach to curbing the escalating landfill burden. Unfortunately, only a mere 20% of plastic waste undergoes proper management. Recently, the construction sector has emerged as a promising domain for integrating recycled materials into concrete, with plastic waste serving as an alternative aggregate[2]. This alternative accounts for a substantial 60 to 70% of the total concrete volume, presenting a practical solution to the plastic waste predicament. Moreover, an increase in the percentage of plastic waste used as an aggregate substitute not only addresses the waste issue but also mitigates the demand for natural aggregates[2]. National standards, advocating for the use of waste and secondary materials, exert political pressure on manufacturers, fostering a culture that intertwines sustainable material use with development[3]. Given the pivotal role aggregates play in concrete characteristics, concerns about natural resource depletion have spurred discussions on the potential adoption of synthetically generated aggregates (crafted from waste) as replacements for natural resources. This groundbreaking study presents a two-pronged approach to address both waste management concerns and the protection of our precious natural resources[3]. By utilizing HDPE and incorporating two unique fillers, sand and rock dust, the researchers have successfully developed a pioneering recycled plastic aggregate. In addition to this innovative material, the study examines the viability of replacing traditional coarse aggregates with recycled plastic aggregates in concrete. Through thorough experimentation with different water-to-cement ratios, the effects of recycled plastic aggregates on the properties of fresh and cured concrete were thoroughly evaluated[4].

For the manufacturing process, high-density plastic (Polyethylene (C2H4) n), natural sand, and rock dust sourced from a local crusher were employed. The waste High-Density Polyethylene (HDPE) was gathered from the AADI plastic manufacturing plant in KUKATPALLY-Hyderabad[8].

**Table:1** Natural sand and rock dust chemical compositions[5]

|  |  |  |  |
| --- | --- | --- | --- |
| Constituent | Quarry rock dust (%) | Natural sand (%) | Test method |
| SiO2 | 61.49 | 81.82 |  |
| Al2O3 | 18.60 | 11.08 |  |
| Fe2O3 | 06.44  | 01.64 |  |
| Cao  | 04.94 | 03.32 |  |
| MgO | 02.45 | 00.77 | IS:4032-1968[5] |
| Na2O  | 00.00 | 01.31 |  |
| K2O  | 03.04 | 01.29 |  |
| TiO2  | 01.35 | 00.00 |  |
| Loss | 00.37 | 00.31 |  |

Using a natural manufacturing approach, we utilized river sand with a particle size of 4.75 mm and adhering to IS 383:1970 grading zone II. Our sand exhibited a specific gravity of 2.63 and a relative bulk density of 1460. To enhance the mixture, we incorporated rock dust with a specific gravity of 2.54 and a relative bulk density of 1745. The result was a plastic aggregate that was remarkably lightweight, weighing in at 650 to 870 kg/m3 and absorbing only a small amount of water, ranging from 0.114 to 0.369 percent. This proved to be an excellent combination for various formulations of recycled plastic sand and recycled plastic rock dust coarse aggregate[8], which were successfully used in our concrete production. The primary manufacturing composition of the plastic aggregates includes Plastic-Sand Aggregates and plastic-rock dust Aggregates, manufactured based on specified proportions[8].

**Table:2** “systematic variation of samples”

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Experiment | Plastic-type | Plastic sand proportion (in grams) | Plastic rock dust proportion (in grams) | Temperature(°C)  | Time (in min) | aggregate weight(dry) in grams |
| Mesh-Shaking-Technique(MST) | HDPE | 1:1(500:500)1:2(500:1000) | 1:1(500:500)1:2(500:1000) | 290-340294-340 | 2535 | 930-9901250-1450 |

Detailed Procedure: Plastic is initially gathered from waste sources and then subjected to shredding, as illustrated in Figure 2a. The following is a step-by-step guide outlining the collection of recyclable plastic. From containers and jars to bottles, plastic bags, and packaging, plastics are available in a variety of shapes and sizes. In order to improve packing, transportation, and distribution of recycled products, it is common for plastics to be broken down into smaller fragments. To cater specifically to plastic bottles and containers, communities typically offer four different types of recycling services, including curbside collection, drop-off points, buy-back initiatives, and deposit or refund programs [8].





 **figure 2a figure 2b figure 2c figure 2d**

Step 2: To determine the weight of the plastic on the scale, begin by placing the scale pointer at the zero level of the top loader. Get rid of any dust particles on the weighing platform. Carefully remove the plastic from the bag and place it onto the scale's tray. Pour the plastic into the tray and take note of the scale reading at eye level[8], to the nearest tenth of a kilogram. Be sure to record the weight of the plastic. Steps 3 and 4: Continuing with Figure 2a, move the plastic into a preheated pan by removing the top loader cover and pouring it in. Step 5: With caution and without directly touching them with bare hands, weigh the sand and rock powder (Fig: 2b). To ensure a smooth and safe process, it is recommended to use paper towels or gloves. Just like with the plastic, follow the weighing steps and accurately record the findings on the report sheet. Once finished, carefully lift the pan off the scale and transfer the sand and rock dust into a preheated pan. Moving on to the next stage (Figure 2a, Steps No-6 and 7), mix the plastic particles thoroughly. Then, continue onto Steps No-8 and 9 (Figure 2a), and carefully apply heat to the pan, allowing the plastic to melt at 294°C.

**Table**:3 physical properties of R-PSCA and R-PRDCA aggregate

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Physical Property** | 1:1-R-PSCA | 1:2-R-PSCA | 1:1-R-PRDCA | 1:2-R-PRDCA |
| Bulk Density (kg/m3) (ASTM C-330-99: table-2) |  653 | 845 | 660 | 867 |
| Absorption (%) | 0.352 | 0.369 | 0.106 | 0.114 |
| Particle Shape | Sub-angular | Sub-angular | Sub-angular | Sub-angular |
| Type | Crushed | Crushed | Crushed | Crushed |
| “Nominal Maximum Size(mm)” | 20 | 20 | 20 | 20 |
| Surface Texture | Partially-rough/ porous | Partially-rough/ porous | Partially-rough/ porous | Partially-rough/ porous |
| Specific Gravity (IS:2386-1963) | 1.42 | 1.57 | 1.42 | 1.56 |
| Color | “Brown” | “Brown” | “brown” | “brown’ |

Manufacturing Procedure: The production of aggregates involved employing the MESH SHAKING TECHNIQUE. Initially, 500 grams of high-density plastic (HDPE) underwent heating on a locally available metallic iron TAWA, starting from room temperature at 27°C. The HDPE was progressively heated until it reached a molten state within the temperature range of 294 to 339°C, as depicted in Figure 2d. For the first mix, 500 grams of sand were used, and for the second mix, 1000 grams were added. The sand was blended into the molten HDPE until a uniform dark paste formed. This mixture was then poured onto a steel mesh, employing a rubbing action to direct the molten mix to fall directly into water. Consequently, aggregates were shaped according to the mesh size, ranging from 2.36mm to 20mm. All temperature readings were meticulously recorded using a thermometer. Safety measures during production included the use of a face mask to mitigate exposure to unhealthy gases released during HDPE burning, as well as safety shoes, gloves, and eyeglasses to minimize the impact of gases on the eyes. Fig. 2c illustrates the produced fire smoke. All aggregates were weighed, exposed to sunlight for drying, and then separated based on sieve sizes ranging from 150 microns to 20mm (sieve analysis conducted).

When it comes to determining bulk density, we rely on the guidelines set forth in IS 2386 (PART III)-1963 and ASTM C330-99: Table 2, which provides Particle Size Distribution Curves for R-PSCA 1:1, R-PSCA 1:2, R-PRDCA 1:1, and 1:2 R-PRDCA. These aggregates are divided into two categories: single-size and well-graded. Our figure depicts the sieve analysis of the coarse aggregate. We ensure that the cumulative percentage passing of the coarse aggregate aligns with ASTM C330/c330M[9] and IS 383-2019, specifically the 1.18-20mm specification. The specific gravity and water absorbency values for both single and well-graded coarse aggregates are as follows: 1.42, 1.57, 1.42, 1.56, and 0.352 percent, 0.106 percent, and 0.114 percent, respectively.

**Microstructure Examination of Aggregates**: The SEM instrument consists of two essential components: the electronic console and the electron column [10]. Governing the instrument's settings are an array of control knobs and switches on the electronic console, which regulate filament current, gear voltage, focus, magnification, brightness, and contrast. By utilizing advanced magnification capabilities, the scanning electron microscope (SEM) allows for the meticulous examination of a wide range of physical and chemical properties, such as size, shape, composition, and crystallography [11]. These controls can all be easily accessed through a computer interface. In order to detect secondary and backscattered electrons, samples are expertly mounted on the stage using a goniometer for secure and precise positioning. When examining plastic aggregate at a microscopic level, it is common for the X-ray detector to be placed close to the sample on one side of the chamber[11]. Through energy-dispersive X-ray spectroscopy (EDX), the focused electron beam is used to generate an X-ray spectrum from the solid sample. This allows for a detailed chemical analysis of a specific region[11].



 1:1 R-PSCA (a) 1:2 R-PSCA (b)

 1:1 R-PRDCA (c) 1:2 R-PRDCA (d)

Figure:6(a)(b)(c)(d) (SEM images of 1:1,1:2,1:1,1;2 plastic sand and rock dust aggregate

"Summarizing the findings, Figure 6(a)(b)(c)(d) presents a microstructural analysis of aggregate mixture samples produced with 1:1, 1:2, 1:1, 1:2 plastic sand, and rock dust aggregates, as observed through SEM imaging. In the case of rock dust, the recycled plastic exhibits robust bonding, attributed to the small particle size, resulting in a high concentration of embedded particles in the plastic matrix, particularly in comparison to other materials[2]. This highlights the effective utilization of HDPE plastic as a binding agent, affirming the accuracy of the aggregate preparation process. Similarly, aggregates made with plastic sand display a sturdy bond between sand particles and HDPE plastic, featuring minimal void spaces. EDX results reveal the presence of C, O, Al, Mg, Si, P, S, K, Ca, Mn, Fe, K, Co, Cu, Zn, and Mo."



Figure:7 EDX or EDA images of 1:1,1:2,1:1,1;2 plastic sand and rock dust aggregate

Materials and Proposed Mix Design Methodology for Concrete with Plastic Aggregates:

In this study, we utilized ordinary Portland cement as the primary binding agent, following the IS: 12269[12] standards. To create a compact aggregate matrix, we used fractions of 1:1-R-PSCA, 1:2-R-PSCA, 1:1-R-PRDCA, 1:2-R-PRDCA, and natural river sand (with a maximum particle size of 4.75mm) as fine aggregates. As for coarse aggregates, we used both single and well-graded sizes. The specific gravities of the coarse aggregates (ranging from 1.18 to 20 mm) were carefully measured as 1.42, 1.57, 1.42, and 1.56, respectively. Moreover, the fine aggregates were found to have a specific gravity of 2.63, as indicated in Table 3 which presents the various properties of the aggregates used in the study. To improve the outcome of the research, a concrete superplasticizer containing a sulfonated naphthalene polymer[13] was utilized.

The aim of this study is to develop an efficient and dependable mix design method that utilizes effective aggregate compaction. This research highlights three important factors in mix design: the ratio of water to cement, the water absorption of additives, and the particle size of additives. The connection between water-cement ratio and the strength of concrete, first established by Abrams in 1919, continues to be a fundamental aspect in modern composite design approaches. However, recent investigations have uncovered an intriguing relationship between strength and water-cement ratio.

The main goal in dosing various aggregate sizes is to reduce the void ratio within the aggregate matrix. To achieve this, several models have been proposed, such as Goltermann et al.'s pack model, De Larrard's compressible packing model[14], and Dewar's particle mixing theory[15]. These models are highly relevant to this approach.

It is crucial to keep in mind that the absolute volume methodology should be utilized if there is variation in the specific gravity of aggregates. To ensure a tightly-packed aggregate matrix, the recommended approach from ASTM C330/C330M and IS 383-2919[6] is to employ a combined grading of aggregates. When it comes to lightweight concrete, ACI 211-98 proposes a mixed proportioning method, based on either weight or volume. For complex mixtures, the design methodology proposed can be broken down into the following stages[3].

The first stage of this study involved carefully selecting and establishing the appropriate water-cement ratio. In order to account for the different aggregates and cement used, ratios of 0.4, 0.6, and 0.65 were chosen [10]. Since specific information was lacking, conservative and estimated values were used [16], following the guidelines set by IS 10262-2019 [17]. These guidelines follow a curve that compares the free water-cement ratio to the 28-day compressive strength ratio. As a result, this research revealed a groundbreaking correlation between the water-cement ratio and the strength of plastic aggregate concrete [16].

In the second stage, the optimal amount of water is determined by referencing ACI 211-98 and considering the specific situation's workability criteria. Typically, the non-air-entrained concrete will have a free water content between 187 kg/m3 and 237 kg/m3. However, this can be reduced by 25% using a 1.5% superplasticizer, such as sulfonated naphthalene polymer concrete mix.

In the third stage, we will find the cement content by using this equation: c = w/(w/c)[3]. This equation takes into account the water/cement ratio (denoted by "w" and determined in stage 1) and provides the cement content in kg/m3

In Stage 4, the procedure calls for the identification of both coarse and fine aggregates. According to the absolute volume method[7], these include plastic sand and plastic rock dust aggregates for the coarse aggregates, and natural river sand for the fine aggregates. To meet the specifications of ASTM C330/C330M(4) and ASTM C33[18] at varying water-cement ratios (0.40, 0.60, and 0.65), four types of coarse aggregates were utilized. It is important to note that non-air-entrained concrete typically contains about 2% entrapped air[16]. Additionally, the total volume of aggregate can be accurately determined using values provided in ACI 211-98 (Table 3.5Between alterations in form and grading of particles, individual changes in dry, loose unit mass play a large role in determining the necessary mortar volume for optimal workability with different types of aggregates"

"In the fifth step, we will determine the appropriate amount of fine aggregate to use in the concrete. Using the measurements for all materials except for the fine aggregate from the previous stage, we will calculate the difference and use that to determine the specific amount needed. By subtracting the total weight of the other elements from the weight of the new concrete, we can establish the precise amount of fine aggregate necessary, based on historical data regarding the weight per unit volume of the concrete."

**Results and discussion**

**Table:4 Mix details for the developed concrete**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| w/c ratio | Sample type | CementKg/m3 | WaterKg/m3 | Fine aggregateKg/m3  | Coarse aggregate Kg/m3 | SuperplasticizerKg/m3 |
| 0.400.600.65 | 1:1 R-PSCA1:2 R-PSCA1:1 R-PRDCA1:2 R-PRDCA1:1 R-PSCA1:2 R-PSCA1:1 R-PRDCA1:2 R-PRDCA1:1 R-PSCA1:2 R-PSCA1:1 R-PRDCA1:2 R-PRDCA | 405405405405290290290290268268268268 | 162162162162174174174174174174174174 | 91877191073699484798681310128651005727 | 471608475624471608475624471608475624 | 4.854.854.854.852.312.312.312.312.122.122.122.12 |

After conducting a visual examination, it was determined that there were no indications of segregation or bleeding in the concrete [3]. According to the accompanying table, the appropriate dosage of superplasticizer was determined. The lesser need for superplasticizer [13] could potentially be attributed to the subangular nature of the aggregates, potentially improving the concrete's workability.

Table 5 provides an in-depth look at the densities of various types of concrete, including fresh, air-dry, and oven-dry densities. Our research suggests that lightweight concrete using synthetic aggregates typically has a plastic density ranging from 1940 to 2113 kg/m3, while standard concrete falls within the range of 2200 to 2600 kg/m3[19]. This clear contrast further highlights the impact of completely replacing traditional coarse aggregates with a combination of recycled plastic sand and coarse rock dust. Our findings also reveal that structural lightweight concrete is typically divided into two categories based on density: those with an air-dry density of less than 2000 kg/m3 and those with a wet density of more than 2000 kg/m3[19]. Based on our study, the air-dry density for the samples ranges from 1941 to 2091 kg/m3.

**Table:5** Densities of the developed concretes.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| w/c ratio | Sample type | Fresh Density(kg/m3) (WGCA) | Fresh Density(kg/m3) (SSCA) | Air-dry Density(kg/m3) (WGCA) | Air-dry Density(kg/m3) (SSCA) |
| 0.400.600.65 | 1:1 R-PSCA1:2 R-PSCA1:1 R-PRDCA1:2 R-PRDCA1:1 R-PSCA1:2 R-PSCA1:1 R-PRDCA1:2 R-PRDCA1:1 R-PSCA1:2 R-PSCA1:1 R-PRDCA1:2 R-PRDCA | 210821332090211120492057198720262005201619952002 | 194219451933194719481968194819611927193319231935 | 206920912051206920102011194119741977198219691971 | 193119391927194119411958193819481919192319181927 |

**Compressive Strength:**

When using structural lightweight concrete, it is crucial to adhere to the minimum compressive strength requirement of 17 MPa. This standard is outlined in ASTM C330, which governs the manufacturing process. When using a water-to-cement (w/c) ratio of 0.40, both single-graded and well-graded aggregate mixtures meet this criterion. However, it is important to note that this is not the case for w/c ratios of 0.60 and 0.65. To better understand the compressive strengths achieved by different types of concrete, refer to Figure 8(a)(b)(c). This visual representation offers valuable insight into the strength capabilities of various concrete mixtures.

When the chart in Figure 8(a) is analyzed, it is observed that the compressive strengths of 1:1 R-PSCA and 1:2 R-PSCA are lower than those of 1:1 R-PRDCA and 1:2 R-PRDCA for a w/c ratio of 0.40 when using single-size coarse aggregate (SSCA). However, interestingly, the compressive strength of well-graded coarse aggregate (WGCA) for 1:2 R-PSCA and 1:2 R-PRDCA yields nearly identical results at 28 days. In a similar manner, for a w/c ratio of 0.60, SSCA demonstrates lower compressive strength for 1:1 R-PSCA and 1:2 R-PSCA, while 1:1 R-PRDCA and 1:2 R-PRDCA exhibit stronger results at 28 days. At a water-cement ratio of 0.65, the difference in strength between the highest (1:1 R-PRDCA and 1:2 R-PRDCA) and lowest (1:1 R-PSCA and 1:2 R-PSCA) compressive strengths at 28 days remains consistent for the same single-graded aggregate. In terms of SSCA and WGCA with a 0.65 w/c ratio (1:1 R-PSCA, 1:2 R-PSCA, 1:1 R-PRDCA, and 1:2 R-PRDCA), the decrease in compressive strength is the least significant.

 **0.40 w/c ratio graph 0.60 w/c ratio graph 0.65 w/c ratio graph**

When comparing SSCA concrete and WGCA concrete, it was found that there was a consistent and minimal variation in compressive strength percentages with varying filler amounts. This suggests that these concrete mixtures, specifically 1:1 R-PSCA, 1:2 R-PSCA, and 1:1 R-PRDCA for a w/c ratio of 0.40 (in both SSCA and WGCA), 1:1 R-PRDCA (in SSCA), and 1:2 R-PSCA, 1:1 R-PRDCA (in WGCA) for a w/c ratio of 0.60, and 1:1 R-PRDCA, 1:2 R-PRDCA (in both SSCA and WGCA) for a w/c ratio of 0.65, all meet the strength requirements set by ASTM C330-04. These results demonstrate the potential suitability of these concrete variations for structural use, as their compressive strength exceeds 17 MPa[16].

**Conclusion:**

Overall, the groundbreaking plastic aggregate shows great potential as a replacement for traditional aggregate due to its lighter weight. This study has yielded important findings, including:

Successful manufacturing of new plastic aggregates from recycled plastics utilizing High-Density Polyethylene (HDPE) and different filler types (HDPE/sand, rock dust).

The new recycled plastic aggregate proves its potential as a complete substitute for traditional materials in concrete by meeting the compliance standards outlined in ASTM C330-04.

Upon examining SEM images, it becomes evident that the material structure is clearly defined, and optical microscope images further corroborate this finding by illustrating a robust bond between the filler and HDPE plastic.

The strength of Single-Size Coarse Aggregate (SSCA) concrete is notably lower than that of Well-Graded Coarse Aggregate (WGCA) concrete, an observation credited to the variation in coarse aggregate size.

This discrepancy in compressive strength is further highlighted by the distinct failure mechanism of crack propagation observed in both SSCA and WGCA concrete. Despite this difference, all types of concrete, including SSCA and WGCA, can still meet the requirements for compressive strength listed in ASTM C330-04 with a water-to-cement ratio of 0.4. As a result, they are suitable choices for various applications such as sidewalks, driveways, and backfilling, where a lower strength is deemed acceptable.

We have developed specific concrete mixtures that fully adhere to the high compressive strength standards outlined in ASTM C330-04. These mixtures have been carefully crafted to achieve a water to cement ratio of 0.60 or 0.65, depending on the type of aggregate used (such as SSCA or WGCA). Our recommended ratios are 1:1 R-PRDCA for SSCA and 1:2 R-PSCA, 1:1 R-PRDCA, and 1:2 R-PRDCA for WGCA. Trust in our proven formulas to deliver outstanding results.

"Despite the existing evidence, it is highly encouraged to conduct further and thorough mechanical sustainability tests, including environmental and economic assessments, in order to fully understand the potential use of plastic aggregates in civil infrastructure."

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