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An Investigation of Mechanical Properties of Concrete by Applying Sand Coating on Recycled High-Density Polyethylene (HDPE) and Electronic-Wastes (E-Wastes) Used as a Partial Replacement of Natural Coarse Aggregates

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Abstract: Plastic wastes are a major hazard for the environment and their use in the construction industry is increasing day by day. The major drawback of the use of plastic in concrete is an exceptional reduction in strength and workability. This research work explores the effect of sand coating on two types of recycled plastic aggregates, high-density polyethylene (HDPE) and electronic-wastes (E-wastes), as partial replacement of natural aggregates. The replacement ranged from 0% to 30% along with the use of super plasticizer SP-675 and wet lock sealant. Both recycled plastic aggregates are crushed, melted, and ground to convert them into aggregates of 20 mm size. The workability of concrete containing uncoated recycled plastic aggregates (HDPE and electronic wastes), SP-675, and wet lock sealant has been found to be higher than controlled concrete samples with 0% recycled aggregates. Compressive strength, split tensile strength, and flexural strength of such type of concrete is lower than the controlled concrete samples due to the weak bond between the plastic aggregates and Ordinary Portland Cement. After applying the sand coating to improve bonding, the workability is reduced compared to uncoated samples whereas the compressive strength, split tensile strength and flexural strength of the sand coated plastic aggregate concrete is higher than uncoated plastic aggregate concrete. There is a significant increase in workability of concrete after the addition of SP-675 when added as 2% by weight of cement. The wet lock sealant positively affects the strength properties of concrete. It is recommended that the durability of concrete containing uncoated and sand coated recycled plastic aggregates be further explored in future studies.

Keywords: electronic wastes; HDPE; sand coating; flexural strength; compressive strength; split tensile strength; SP-675; wet lock sealant

1. Introduction

Concrete is a mixture of cement, sand, natural coarse aggregates (NCA), water, and admixtures. The main reasons for the extensive use of concrete in the construction industry are its strength properties, durability, versatility, and its ability to be cast into any desired shape on site. NCA is a major part of concrete, and it contributes significantly to concrete strength. Presently, many countries around the world are facing a deficiency of NCA, importing a huge quantity to fulfill their needs [1]. With increasing population and urbanization, the demand for concrete in the construction sector is increasing, resulting in the massive use of NCA in concrete. There is a need to preserve raw materials to reduce the effects of climate change and the depletion of natural resources [2,3]. For this purpose, different efforts have been made in the recent past to partially substitute NCA with different kinds of waste products including plastic wastes such as electronic waste (E-wastes) [4–8], polyethylene terephthalate (PET), and high-density polyethylene (HDPE) [9,10], etc. Therefore, research on the use of various alternatives in place of NCA is on the rise. There has been significant work being carried out on the use of recycled aggregate concrete [11,12]. However, the demand of the construction industry may not be fulfilled by demolished waste only and there is a need to explore other alternatives. Several studies have been carried out on solid wastes such as different types of plastics [13], paper or cardboard [14], E-waste [15], glass [16], crushed asphalt [17], beer green glass and tiles [18], animal bones, and human hair [19] in concrete.

2. Literature Review

Jaivignesh and Sofi [20] concluded that upon the addition of plastic wastes in concrete the reduction of hardened properties of concrete was noticed while the workability of concrete improved. Zainab and AL-Hashmi used a combination of 80% polyethylene and 20% polypropylene in the range of 5, 10, 15, 20% by volume of fine aggregate in concrete and concluded that again reduction in mechanical properties and density of concrete was found, while workability increased with an increase of the plastic content in concrete [21]. Habib et al. concluded that addition of HDPE in the range of 5, 10, 15, 20% resulted in reduction of mechanical properties of concrete while workability was increased [9]. Rathore and Rawat noticed the same trend upon addition of E-wastes in concrete [22]. A similar trend was found by Nursyamsi et al. upon increasing content of HDPE in concrete [23]. Amalu et al. concluded from test results of compressive strength and flexural strength of concrete with waste plastic aggregates that both properties decreased with increasing ratios of waste plastic aggregates in concrete. However the workability of such type of mix increased due to less water absorption [24]. Manhal and Farah also noticed the decrease in compressive strength, split tensile strength, and modulus of rupture of concrete upon the addition of recycled plastics in concrete. The mode of failure of concrete containing waste plastics was brittle and not recommended for structural applications [25]. Fahad et al. found that 100% incorporation of recycled plastic aggregates with natural aggregates into the concrete resulted in about 13% reduction in chloride penetration and compressive strength of concrete. The concrete containing recycled plastic aggregates had more durability than the natural coarse aggregate concrete due to the reduction in chloride penetration which was due to less permeability of recycled plastic aggregate concrete [10]. Ullah et al. concluded that there was a reduction in compressive strength, split tensile strength, sportively coefficient, ultrasonic pulse velocity (UPV) value, and abrasion loss upon increasing content of E-wastes in concrete. However, durability and workability values increased by increasing E-waste content in concrete. Concrete with E-wastes showed better performance against alternate wetting and drying cycles as compared to normal concrete [26].

Ali et al. used E-wastes in the range of 10, 15, and 20% by volume of fine aggregates in concrete. In addition, a silica fume was added into the concrete with waste plastics as partial replacement of cement in the range of 10, 15, and 20% by volume. He found that the addition of silica fume in concrete with E-wastes reduced the effect of plastic waste on concrete strength. The compressive strength and split tensile strength of E-waste concrete with silica fume were reduced to only 4.7% and 1.1% respectively. On the other hand, workability was reduced upon the addition of silica fume in E-waste concrete. Also, the thermal properties of concrete with silica fume and E-wastes were improved [27]. Singh and Patel used E-wastes in concrete in the range of 10, 15, and 20% by weight of NCA. The addition of fly ash in E-waste concrete was also carried out in the range of 10, 15, and 20%

by volume of cement to check its effect on concrete strength and other properties. They concluded that the addition of fly ash in E-waste concrete caused some improvement in compressive strength and workability [28]. Gupta and Singh used PET in the range of 10, 20, and 30% by volume of NCA. The PET was treated with a ground granulated blast furnace slag (GGBS) solution to improve their performance in concrete. They concluded that treatment of PET with GGBS caused some increase in compressive strength of concrete than other concrete with untreated PET. However, there was no effect of GGBS treatment of PET on flexural strength of concrete while the workability of concrete with GGBS treated PET was also increased [29].

Ahmed and Qureshi used E-wastes in concrete as a partial replacement of NCA as 30% by volume. In addition, 0.75% polypropylene macro synthetic fibers were also added in concrete to enhance its strength. An increase in compressive strength and split tensile strength values of concrete with E-wastes was reported as 30% and 75%, respectively, due to the addition of 0.75% macro synthetic fibers. There was a slight increase in the density of concrete with E-wastes due to the addition of macro synthetic fibers [30]. Rai et al. used virgin plastic pallets in the range of 5, 10, and 15% by volume of fine aggregates in concrete. To strengthen the concrete with virgin plastic pallets, CONPLAST SP320 was added to enhance compressive strength and workability. The results indicated that compressive strength and workability of concrete with virgin plastic pallets were increased while there was no effect of super plasticizer on flexural strength of concrete with virgin Plastic pallets [31]. Lee et al. conducted SEM on concrete with recycled plastic wastes to check the reason for decreased strength of such type of concrete. The results of SEM indicated that decreased strength properties of concrete with recycled plastic wastes was due to weak bonding between cement paste and recycled plastics and hydrophobic nature of plastic wastes in concrete [32].

In this research study, we tried to incorporate recycled plastic aggregates in concrete to check their effect on the workability and mechanical properties of concrete. Previous studies revealed that the strength properties of concrete decreased upon addition of recycled plastic aggregates in concrete when compared to conventional concrete due to the weak bonding between the cement paste and recycled plastic aggregates. There is a need to improve bonding between cement paste and recycled plastic aggregates and for this purpose, sand coating of recycled plastic aggregates was carried out. Two types of recycled plastic aggregates named high density polyethylene (HDPE) and electronic wastes (E-wastes) were used in concrete to make a comparison, and the effect of two diverse types of plastics obtained from different resources on different properties of concrete.

3. Materials and Methods

Ordinary Portland cement (i.e., Best Way cement) was used in this research study. Different tests were performed to determine the properties of Ordinary Portland cement. The results of different tests conducted on cement such as the soundness test by Le-Chatelier apparatus, normal consistency, and test for initial and final setting time by Vicat apparatus etc. are presented in Table 1. The chemical properties of cement were provided by the manufacturer (also listed in Table 1).

Ordinary tap water was used for the preparation of concrete mixes. The water was free from all types of impurities and organic matter. Fine sand obtained from local quarries was used. Natural coarse aggregates used for the preparation of concrete mixes were Sargodha Crush. The particle sizes of coarse aggregates range from 4.75 mm to 20 mm. In this study, two types of recycled aggregate plastics were used, namely high-density polyethylene plastic (HDPE) and electronic wastes. HDPE plastics included were plastic bottles, plastic canes, toys, corrosion-resistant piping, geo-membranes, plastic lumber etc. as shown in Figure 1. Electronic wastes included were scraps of laptops, TVs, computers, refrigerators parts, LCDs, monitors, and printers as shown in Figure 2.

Table 1. General properties of Portland cement.

Chemical Properties	Percentage (%)	Physical Properties	Result
SiO_2	23.21	Specific gravity	2.49
Al_2O_3	4.93	Specific surface (m^2/kg)	320
Fe_2O_3	3.87	Consistency	27%
CaO	64.78	Initial setting time	89 min
MgO	2.76	Final setting time	219 min
SO_3	2.94	Soundness	8 mm
Na_2O	0.24	Compressive strength (28-days)	25.2 MPa
K_2O	0.78	Fineness	91.2%
		Loss on ignition	0.62

Figure 1. Discarded plastic scrap on left (**A**) and its conversion into HDPE shown on right (**B**).

Figure 2. Discarded computer scrap on left (**A**) and its conversion into E-wastes on right (**B**).

General properties and sieve analysis of varied materials used in this research study are presented in Table 2 and Figure 3.

Table 2. General Properties of aggregate materials.

Properties	Cement	Sand	Coarse Aggregate	HDPE	Electronic Waste	Super Plasticizer
Nominal Size	50 µm	−4%	20 mm	20 mm	20 mm	-
Water Absorption	-		4.75%	3.40%	3.40%	-
Specific Gravity	3.15	2.67	2.85	0.97	1.04	1.150
Bulk Density (kg/m^3)	1440	1600	1602	531.6	476	-
Fineness Modulus		2.2	2.1	1.79	1.68	-
Morphology			-	-	-	Brown Liquid
Abrasion Value	-	-	1.32%	7.24%	6.68%	-
Impact Value	-	-	11.43%	2.66%	3.29%	-
Shape	-	-	Angular	Angular	Angular	-

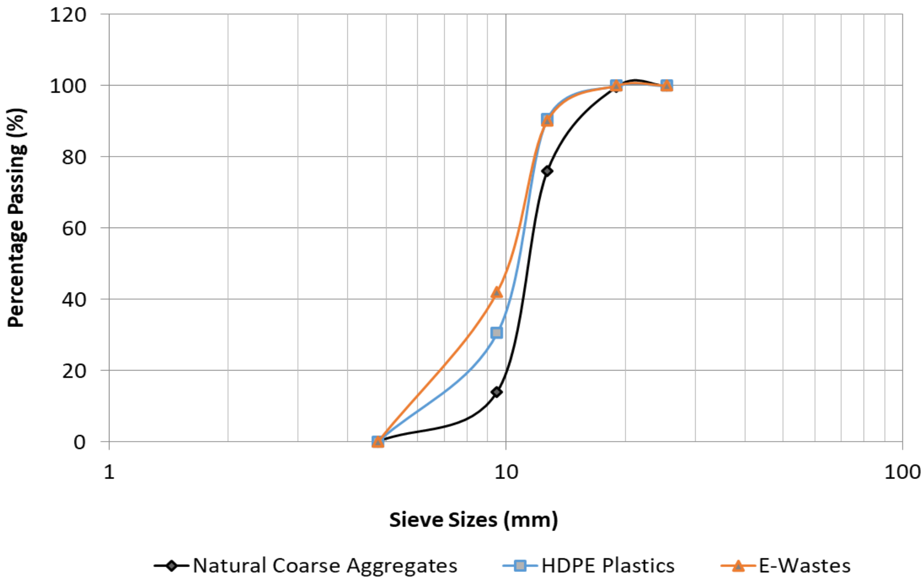

Figure 3. Particle size distribution curve for natural and plastic aggregates.

The strength of concrete is mainly dependent on the bond between cement paste and aggregates. Although aggregates occupy a major volume of concrete matrix, at the same time weak bond between cement paste and coarse aggregates results in a reduction in the strength of the concrete. As far as conventional concrete is concerned, it is made with natural coarse aggregates in which the bond development between cement paste and natural aggregates is better as compared to the bond between cement paste and recycled plastics HDPE and E-wastes (which are hydrophobic and have excess water around the surface of recycled plastics, causing hindrance in bond development between cement paste and recycled plastics). It can be seen from Table 2 that impact value of natural coarse aggregates is greater than recycled plastics HDPE and E-wastes indicating that natural coarse aggregates are more tough with better ability to bear shocks and vibrations as compared to HDPE and E-wastes.

Sand coating of both types of recycled plastics was carried out in hot sand. Firstly, the sand was heated in a pan for 10 min and after that sand coating of both types of recycled plastics was carried out after placing them in hot sand and mixing them properly until the whole surface of recycled plastics was completely covered with sand. The coated shapes of both types of plastics are shown in Figure 4. The purpose of the sand coating was to improve the bonding interface between the cement and recycled plastic aggregates.

Figure 4. (**A**) E-waste and (**B**) HDPE aggregates after sand coating.

Both types of plastics were purchased from the local market and were converted into aggregate form after four distinct stages. The first step was the washing of both types of plastics to remove dust and clay particles from the surface of plastics. The second step was the crushing of all plastics used for the preparation of HDPE and E-wastes with the help of an electric crusher. The final shape of plastics after crushing is small flakes and shredded particles. The third stage was the melting of shredded plastics in the kiln at the temperature of 200 °C. The next stage was the cooling of both types of plastics in water until plastic rocks were formed. The final stage was the crushing of plastic rocks into the shape of plastic aggregates. Figure 5 shows the schematic diagram for the manufacturing of plastic aggregates.

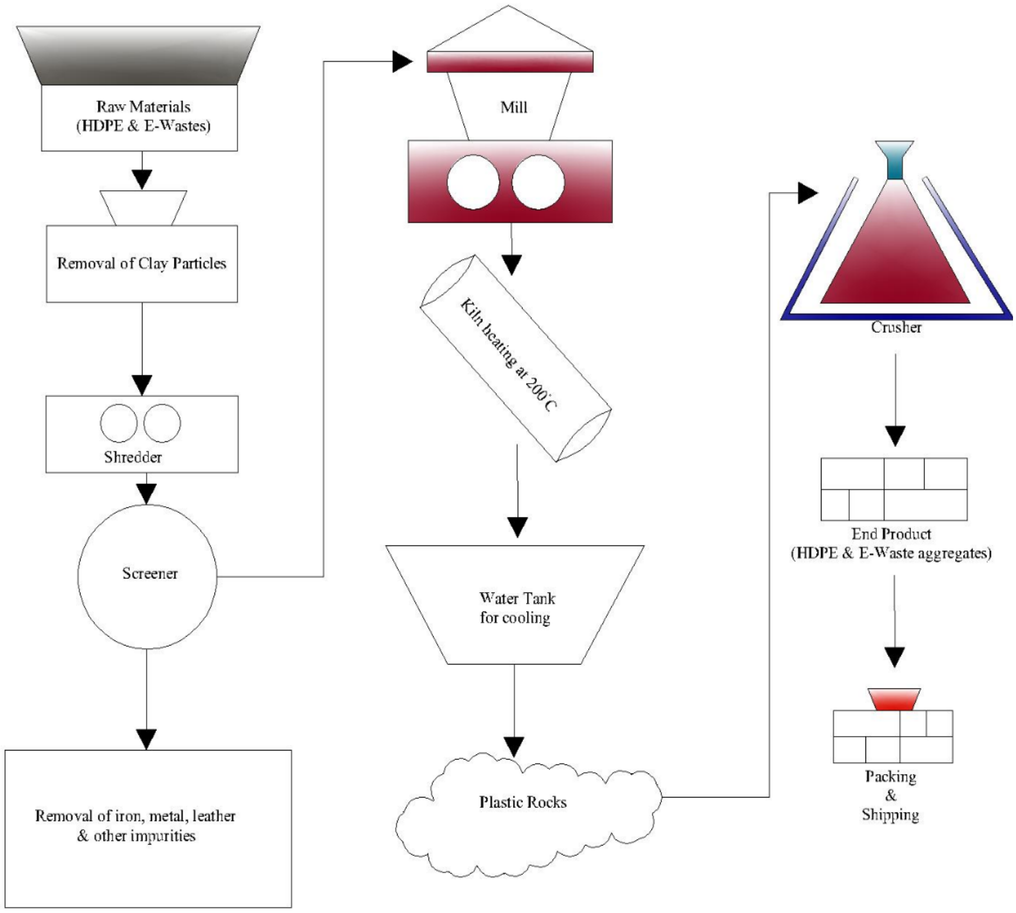

Figure 5. Schematic diagram of the manufacturing process of HDPE and E-wastes.

4. Development of Experimental Setup

Past studies revealed that the use of plastics in concrete resulted in a decrease in strength properties and that such types of concrete are not suitable for load-bearing structures. The reason is the poor bonding between the cement and plastic aggregates which results in decreased strength and brittle behavior of recycled plastic aggregate concrete. To enhance the strength of concrete containing recycled plastics sand coating of the surface of recycled plastics was carried out to improve the bonding properties of cement and recycled plastic aggregates. A super plasticizer named SP-675 is used at the rate of 2% by weight of cement for improving workability and a wet lock sealant is used at the rate of 2 kg per 50 kg bag of cement to increase the strength properties of concrete containing recycled plastic aggregates. A total of 30 concrete cylinders of size 150 × 300 mm and 15 concrete beams of 2 ft length and 3.5 × 4 inches cross-section were considered including control mixes and 10%, 20%, and 30% replacement of natural coarse aggregates with HDPE and E-wastes as a partial replacement with or without sand coating on the surface of HDPE and E-wastes aggregates. The details of the concrete mixes are shown in Table 3.

Table 3. Details of concrete mixes types, detail, list of components, sealant, and plasticizer's detail.

Mix ID	Description	Cement	Natural Sand	Coarse Aggregate	Water	HDPE	E-Wastes	Wetlock-Sealant	Plasticizer (SP-675)
		(kg)	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)
Control	Reference Samples (Cylinders and beams)	19.962	33.264	66.609	9.981	0	0	0.798	0.40
C10%-EW	Replacement of 10% coarse aggregates with EW	26.616	44.352	79.932	13.308	0	2.64	1.065	0.532
C10%-HDPE	Replacement of 10% coarse aggregates with HDPE	26.616	44.352	79.932	13.308	2.95	0	1.065	0.532
C20%-EW	Replacement of 20% coarse aggregates with EW	26.616	44.352	71.052	13.308	0	5.28	1.065	0.532
C20%-HDPE	Replacement of 20% coarse aggregates with HDPE	26.616	44.352	71.052	13.308	5.89	0	1.065	0.532
C30%-EW	Replacement of 30% coarse aggregates with EW	26.616	44.352	62.172	13.308	0	7.91	1.065	0.532
C30%-HDPE	Replacement of 30% coarse aggregates with HDPE	26.616	44.352	62.172	13.308	8.84	0	1.065	0.532

The concrete mix ratio used for current research work is 1:1.5:3. The water cement ratio adopted is 0.50. Four types of tests are performed on concrete samples to determine the fresh and hardened properties of concrete made with two types of recycled plastic aggregates (HDPE and electronic wastes). The total number of samples tested in the current study along with standards is shown in Table 4.

Table 4. Testing details expressing the types (purpose), adapted standard, and number of samples prepared.

Test Type	Standard Used	Specimen Shape	Age (Days)	No. of Samples			
				HDPE and E-wastes (Uncoated and Coated)			
				0%	10%	20%	30%
Slump	ASTMC143/C143M [33]	Cone	Immediately after mixing	3	6	6	6
Compressive strength	ASTMC39/C39M [34]	Cylinder	28	3	12	12	12
Split Tensile Strength	ASTMC496/C496M-17 [35]	Cylinder	28	3	12	12	12
Flexural Strength	ASTMC239 [36]	Cylinder	28	3	12	12	12

5. Testing Procedures on Materials

Angiolilli, M.; Gregori, A.; Vailati, M. [37] discussed the effect of short glass fibers in lime-based mortar to study their effect on different mechanical properties of lime-based mortar. Three point bending test was performed on beams with size 160 × 40 × 40 mm size to determine their flexural strength. The broken pieces of tested beams were tested for compression and split tensile strength tests to remain uniformity of results. All tests were performed in hydraulic displacement-controlled testing machine. The results concluded that fibers used in lime mortar increased the mechanical properties of lime-based mortar. In addition to that ductility of lime-based mortar was also increased. They concluded that sustainable materials can be used for masonry strengthening. Vailati, M.; Mercuri, M.; Angiolilli, M.; Gregori, [38] discussed the use of Sisal short fibers in lime-based mortar. Mortar samples were tested in three point bending assembly. Compressive strength and split tensile strength test were also performed on broken beam samples. comparison was made between unreinforced and reinforced sisal fiber lime-based mortar and results showed that used of short sisal fibers is recommended for retrofitting of old buildings.

6. Results and Discussion

This section covers the workability and mechanical properties (compressive strength, split tensile strength, and flexural strength) as well as the supporting reasons that brings the trends in results.

6.1. Workability

The workability of concrete with HDPE and E-wastes was determined by slump cone test as per ASTMC143/C143M [33] and the results of the tests of all concrete mixes are shown in Figure 6. From workability results, it was revealed that the workability of concrete mixes increased with an increase in the replacement ratio of uncoated recycled plastic aggregates (HDPE and E-wastes) in concrete. The increase in workability of concrete with uncoated HDPE and E-wastes was attributed due to increase in free amount of water and negligible water absorption by HDPE and E-wastes due to their hydrophobic nature. The trend for increase in workability values was also observed in past [6,39]. Similar trend was also observed in research study conducted by M.F. Javaid, M. I. Qureshi, S. Saleem [40] concluded that increase in workability of concrete with recycled plastics with increase in replacement levels of plastics. The slump value included between 0 and 40 mm is good for a foundation. In any case the slump value for structural applications cannot be greater than 100 mm. the slump value in the range of 0 to 25 mm is preferred for road sections and also used in vibrated concrete sections while higher value of concrete greater than 100 mm is adopted in clogged concrete sections [41] and in precast concreting techniques also. The workability values goes on decreasing once the sand coated recycled plastics HDPE and E-wastes were used in concrete. The decreased workability values were attributed due to the change in nature of plastic aggregates from hydrophobic to hydrophilic due to the deposition of sand onto their surface which not only improves bonding properties with cement paste but also absorbs more water as compared to uncoated plastics which have more water repulsion and hydrophobic.

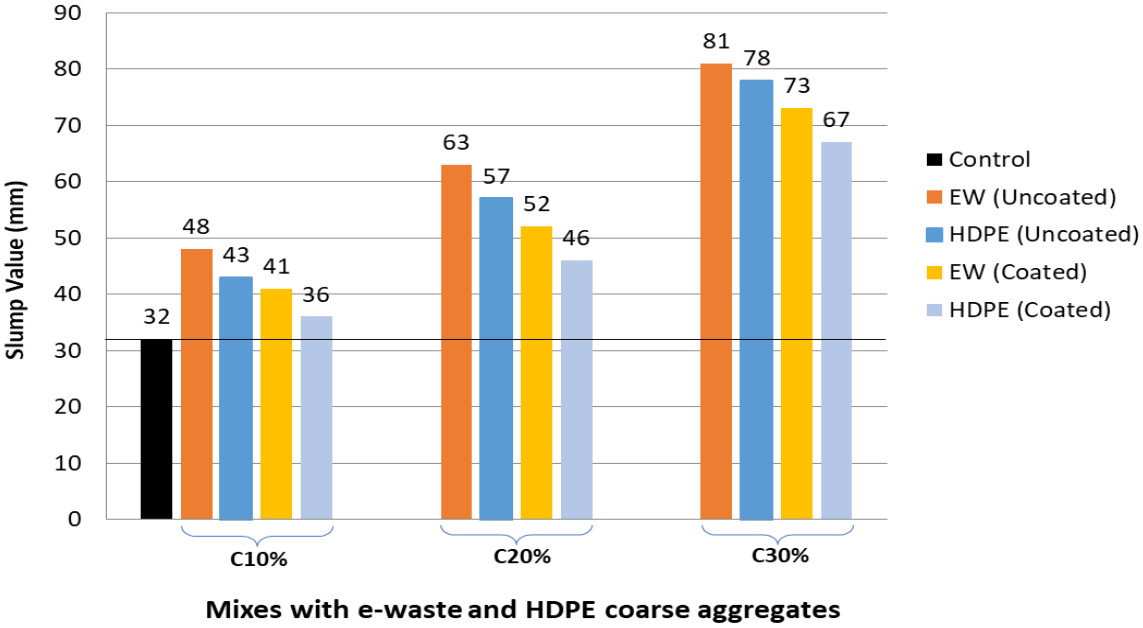

Figure 6. Comparison of Slump tests against 10%, 20%, and 30% replacements of original aggregates and comparison with the control case.

6.2. Mechanical Properties

The study also covers the compressive strength, split tensile strength, and flexural strength analysis of all samples.

6.2.1. Compressive Strength

The compressive strength test was performed following ASTM C39/C39M guidelines [34]. A total of 39 concrete cylinders with size 150 × 300 mm were casted and cured for 28 days as shown in Figure 7. The cylinders were capped with Plaster of Paris on their top surfaces to ensure application of uniform loading by platen of a machine on the top surface of cylinders. The compressive strength of all concrete cylinders was determined by a compression testing machine of 3000 kN capacity as shown in Figure 8.

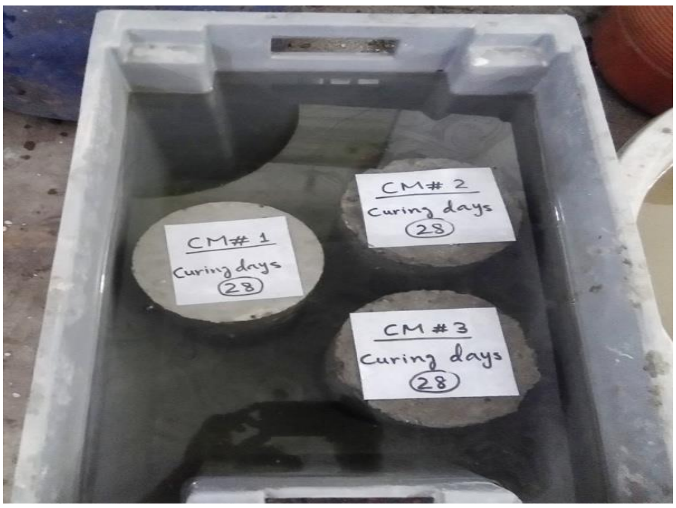

Figure 7. Placement of concrete cylinder in water tab for 28 days curing.

Figure 8. Placement of concrete cylinder in compression testing machine.

The diameter of concrete cylinder is 150 mm while the diameter of upper and lower platens of compression testing machine 305 mm and 228 mm. For the application of uniform load by compression testing machine, capping of plaster of Paris was carried out on the surface of concrete cylinder. Load applied on the surface is concentric and machine gives failure load as well as compressive strength.

The failure modes of concrete samples after compression test with recycled plastics HDPE and E-wastes are shown in Figure 9.

Figure 9. Failure mode of concrete cylinders with recycled plastics after compression test.

Figure 10 shows the variations in compressive strength of concrete mixes against different percentages of two types of recycled plastic aggregates used as a partial replacement of NCA. The compressive strength of control mix concrete is 35.6 MPa, while compressive strength values of concrete containing 10%, 20% and 30% uncoated HDPE used as a partial replacement of coarse aggregates are 28.1 MPa, 21.6 MPa, and 18.8 MPa, respectively. The compressive strength values of concrete mixes with10%, 20%, and 30% uncoated E-wastes used as a partial replacement of coarse aggregates are 31.4 MPa, 26.4 MPa, and 22.95 MPa, respectively. The decrease in compressive strength values is more for the concrete containing uncoated HDPE than uncoated E-wastes. The decrease in compressive strength values of concrete containing uncoated HDPE was found to be 21%, 39%, and 47% for the replacement levels of 10%, 20%, and 30%, respectively. This trend for a decrease in compressive strength values was found to be lesser for concrete containing uncoated E-wastes where the decrease was found to be 12%, 26%, and 36% for the replacement level of 10%, 20%, and 30% of NCA.

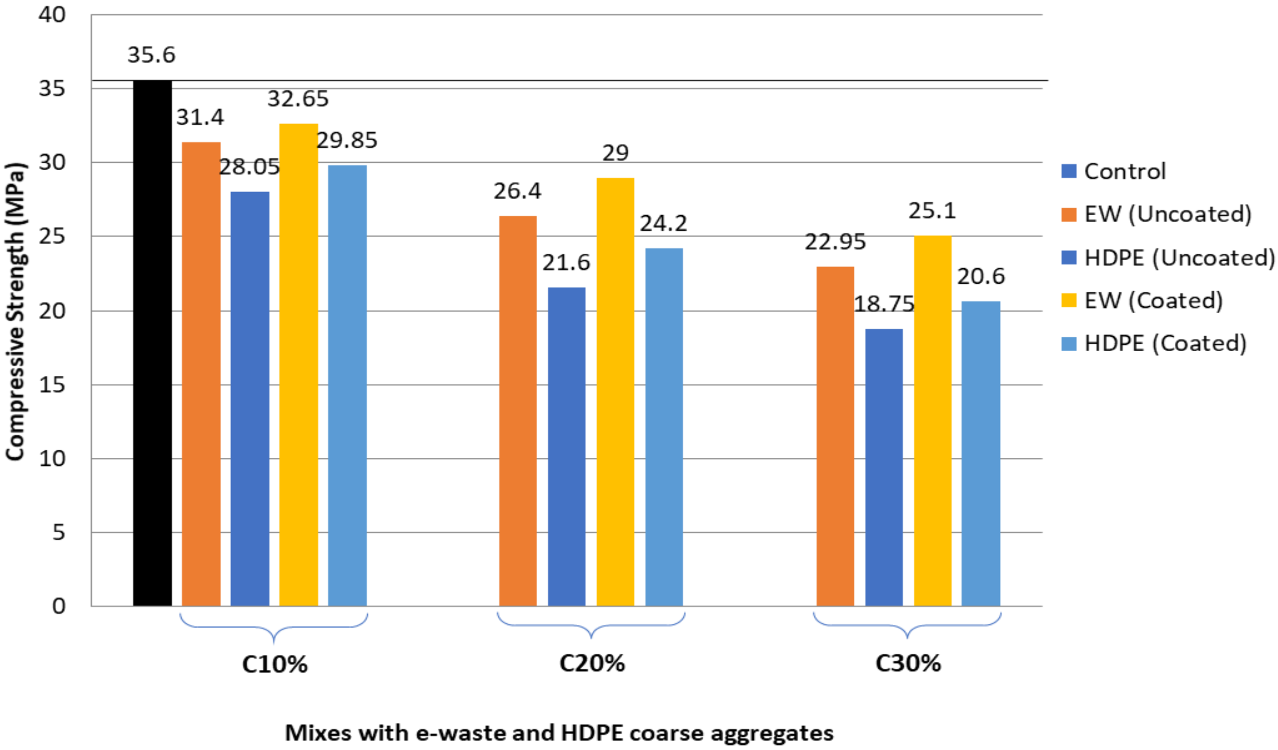

Figure 10. Comparison of compressive strength values of concrete mixes with control sample and concrete containing uncoated and coated recycled plastics.

The decrease in compressive strength values was due to the weak bond between cement paste and recycled plastic aggregates and due to the hydrophobic nature of recycled aggregate particles. This was noticed in past studies. M.J. Islam, M.S. Meherier, A.K.M.R. Islam [42] found that plastics are hydrophobic and water absorption of recycled plastics was almost zero resulting in excess water around the plastic aggregates. This excess water will form a film around plastic aggregates resulting in a weak bond between cement paste and recycled plastics. L. Pezzi, P.A. De Luca, D. Vuono, F. Chiappetta, A. Nastro [43] observed the large cracks between cement paste and recycled aggregates along with water film through scanning electron microscope (SEM) results which caused a weak bond between cement pates and plastic aggregates causing decrease in strength. From past studies K. Hannawi, S. Kamali-Bernard, W. Prince [44] concluded that weak bonding between cement paste and recycled plastic aggregates was the main cause of decrease in strength properties of concrete. S.C. Kou, G. Lee, C.S. Poon, W.L. Lai [45] conducted scanning electron microscope (SEM) test of concrete with recycled plastics and found a weak interfacial transition zone between cement matrix and recycled plastics. Recycled plastic aggregates can be manually removed from cement matrix. Similar findings were reported by many researchers that upon addition of plastic aggregate, compressive strength of concrete reduces as compared to conventional concrete [46–50].

There was a need to improve bonding between cement paste and recycled plastic aggregates surfaces. For this purpose, sand coating of recycled plastic aggregates was carried out. The sand was heated for 10 min and both recycled plastic aggregates were put in hot sand and properly mixed until the sand particles were deposited on the surfaces of both recycled plastics. Sand coated plastic aggregates were used in concrete mixes in the same percentages (i.e., 10%, 20%, and 30%) as a partial replacement of NCA. The compressive strength values of concrete mixes with sand-coated plastic aggregates were found to be higher than concrete mixes with uncoated plastic aggregates.

The compressive strength values of concrete containing sand coated plastic aggregates were lesser than control concrete mix. Further, the compressive strength values for the concrete containing sand-coated plastic aggregates were improved due to improvement in the bonding interface between cement paste and recycled plastic aggregates and due to the hydrophilic nature of recycled plastic aggregates. Comparison of compressive strength values of control concrete mix, concrete containing uncoated, and sand coated recycled plastic aggregates is shown in Figure 10 and percentage reduction in compressive strength variation of concrete mixes with HDPE/E-wastes are shown in Figure 11.

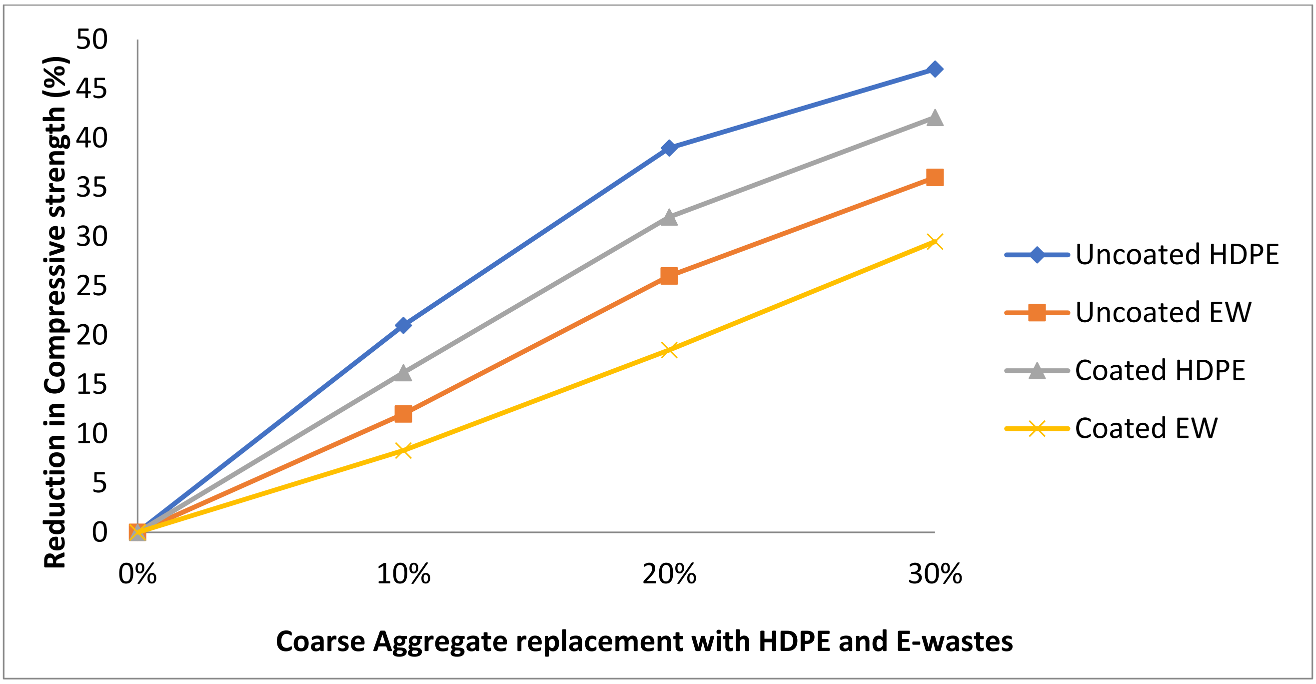

Figure 11. Graph shows reduction in compressive strength with E-wastes/HDPE (coated and uncoated) variation in concrete.

6.2.2. Split Tensile Strength

Split Tensile strength test was performed following ASTM C496/C496M-17 guidelines [35]. A total of 39 concrete cylinders with a size of 150 mm × 300 mm were casted and cured for 28 days. The split tensile strength of all concrete cylinders was determined by a compression testing machine of 3000 kN capacity as shown in Figure 12.

Figure 12. Placement of concrete cylinder in compression testing machine for split tensile strength test.

Failure modes of concrete samples after split tensile strength test with recycled plastics HDPE and E-wastes is as shown in Figure 13.

Figure 13. Failure mode of concrete cylinders with recycled plastics after split tensile strength test.

Figure 14 shows the variation in split tensile strength of concrete mixes against different percentages of two types of recycled plastic aggregates used as a partial replacement of NCA. The split tensile strength of control mix concrete is 4.53 MPa, while the split tensile strength values of concrete containing 10%, 20% and 30% uncoated HDPE used as a partial replacement of coarse aggregates are 3.8 MPa, 3.15 MPa, and 2.55 MPa respectively. The split tensile strength values of concrete mixes with10%, 20% and 30% uncoated E-Wastes used are 3.9 MPa, 3.55 MPa, and 3.0 MPa, respectively. The decrease in split tensile strength values is more for the concrete containing uncoated HDPE than uncoated E-wastes. The decrease in split tensile strength values of concrete containing uncoated HDPE was found to be 16.1%, 30.5%, and 43.7% for the replacement levels of 10%, 20%, and 30%, respectively. This trend for a decrease in split tensile strength values was found to be lesser for concrete containing uncoated E-wastes where the decrease was found to be 13.9%, 21.6%, and 33.8% for the replacement level of 10%, 20%, and 30% of natural coarse aggregates.

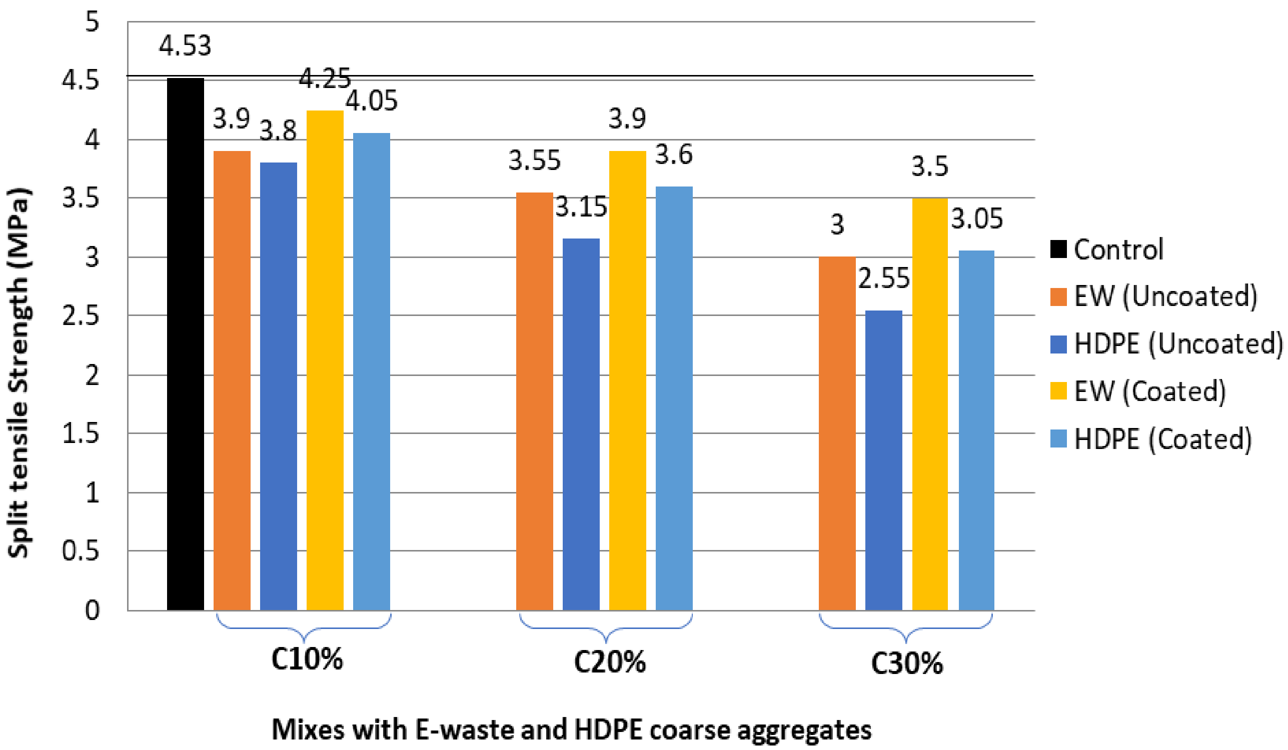

Figure 14. Comparison of split tensile strength values of concrete mixes with control sample and concrete containing uncoated and coated recycled plastic.

Again, the weak bonding and hydrophobic nature of recycled plastics are the main reasons for the decreased split tensile strength values of all concrete mixes. Sand coating of recycled plastic aggregates was carried out to improve the bonding properties of recycled plastics and cement paste. Sand coated plastic aggregates were used in concrete mixes in the same percentages i.e., 10%, 20%, and 30% as a partial replacement of coarse aggregates. The split tensile strength values of concrete mixes with sand coated plastic aggregates were found to be higher than concrete mixes with uncoated plastic aggregates as shown in Figure 14. But the split tensile strength values of concrete containing sand coated plastic aggregates were lesser than control concrete mix.

There was a slight improvement in the split tensile strength values of concrete with sand-coated recycled plastics.

Comparison of split tensile strength values of control concrete mix, concrete containing uncoated and coated recycled plastic aggregates is shown in Figure 14 and with percentage reduction in split tensile strength are shown in Figure 15.

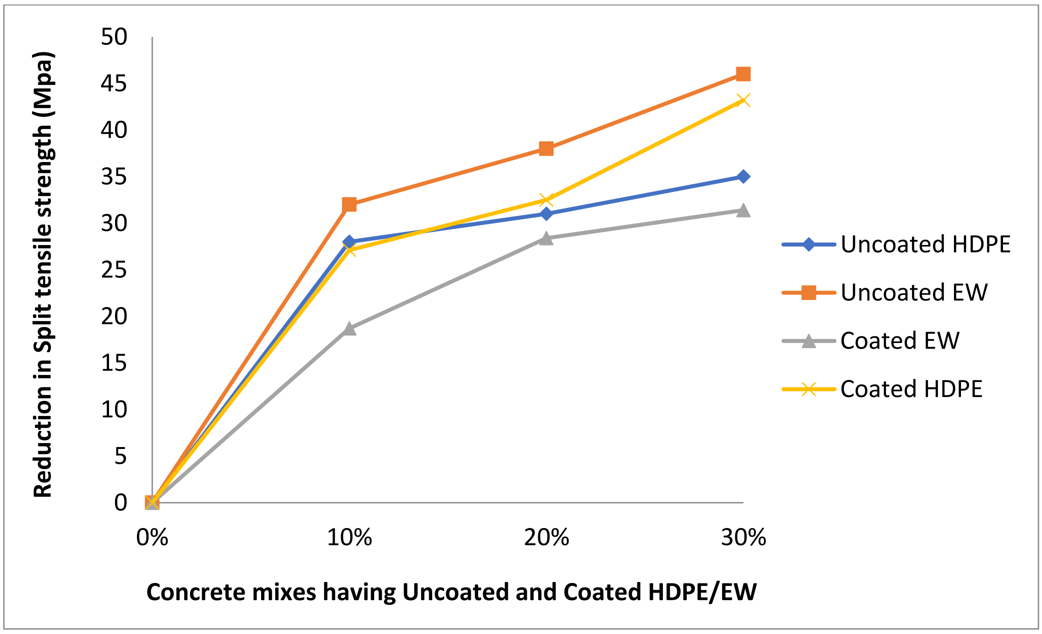

Figure 15. The graphs shows % reduction in split tensile strength with E-wastes/HDPE (coated and uncoated) variation in concrete.

6.2.3. Flexural Strength

The flexural strength test was performed following ASTM C293 guidelines [36]. A total of 39 simple beams with a length of 2 ft and cross-section 3.5 × 4 inches were casted and cured for 28 days as shown in Figure 16.

Figure 16. Simple concrete beams for flexural strength test.

The flexural strength of all simple beams was determined using central point loading assembly placed in the flexural testing machine of 600 kN capacity Figure 17.

Figure 17. Central point loading assembly for flexural strength test on left (**A**), and beam with central point loading assembly placed in the flexural testing machine on right (**B**).

The failure modes of specimens of concrete beams with recycled plastics after flexure strength test are shown in Figure 18.

Figure 18. Failure mode of concrete beams with recycled plastics after flexural strength test.

Figures 19 and 20 show the variation in flexural strength of concrete beams against different percentages of two types of recycled plastic aggregates used as a partial replacement of natural coarse aggregates and percentage reduction in flexural strength against different replacement levels of HDPE and E-wastes. The flexural strength of control mix concrete is 7.33 MPa, while flexural strength values of concrete containing 10%, 20%, and 30% uncoated HDPE used as a partial replacement of NCA are 5.02 MPa, 4.57 Mpa, and 3.98 Mpa, respectively. The flexural strength values of concrete mixes with10%, 20%, and 30% uncoated E-wastes used as a partial replacement of coarse aggregates are 5.24 MPa, 5.06 Mpa, and 4.78 Mpa, respectively. The decrease in flexural strength values is more for the concrete containing uncoated HDPE than uncoated E-wastes. The reduction was 32%, 38%, and 46% for concrete with uncoated HDPE. On the other hand, the reduction was 28%, 31%, and 35% for concrete with uncoated E-wastes.

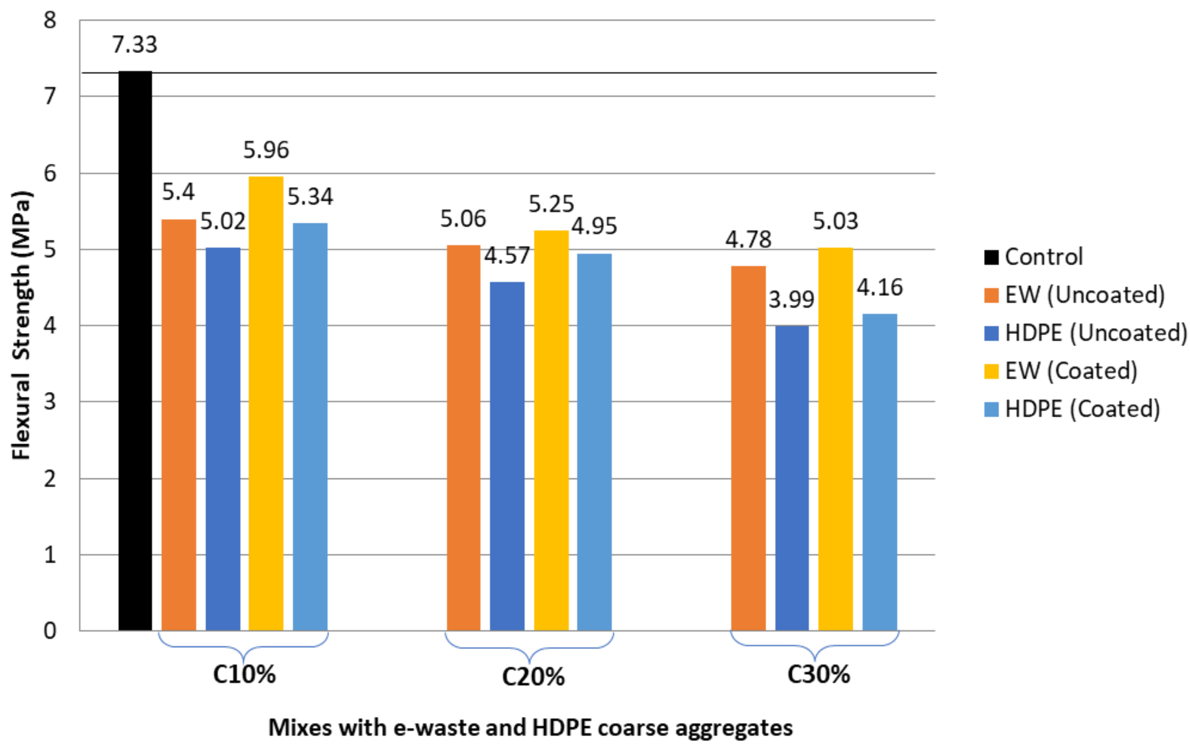

Figure 19. Comparison of flexural strength values of concrete mixes with control sample and concrete containing uncoated and coated recycled plastic.

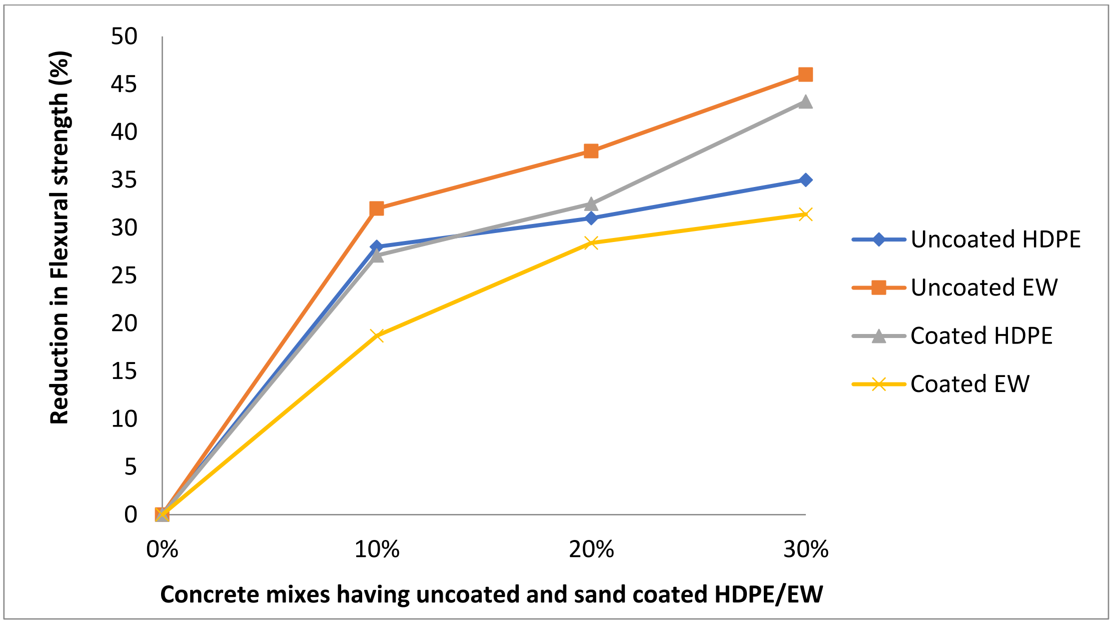

Figure 20. Percentage reduction in flexural strength with E-wastes/HDPE (coated and uncoated) variation in concrete.

Sand coated plastic aggregates were used in concrete mixes in the same percentages (i.e., 10%, 20%, and 30%) as a partial replacement of coarse aggregates. The flexural strength values of concrete mixes with sand-coated plastic aggregates were found to be higher than concrete mixes with uncoated plastic aggregates. But the flexural strength values of concrete containing sand coated plastic aggregates were lesser than control concrete mix. Further, the drop in flexural strength values for the concrete containing sand coated plastic aggregates was reduced due to improvement in the bonding interface between cement paste and recycled plastic aggregates and due to the hydrophilic nature of recycled plastic aggregates.

One thing is very important that when plastics HDPE and E-wastes were used in concrete either uncoated or sand coated there were some in homogeneity of concrete mix which was clearly seen in Figure 17. The homogeneity of the mix appeared on the surface of concrete beams was due to the reason of poor bonding between cement paste and recycled plastics due to their hydrophobic nature with no attraction of water. This excess water will form a film around the plastics causing hindrance in making bond with cement as revealed in previous studies [42–50]. As a result of sand coating there was some improvement in bonding between cement paste and recycled plastics resulting in less in homogeneity and segregation.

7. Statistical Correlation among Various HDPE and E-Wastes Concrete Properties

Different experimental parameters are correlated with the help of statistical correlation as carried out in the past [51]. In statistical correlation the effect of one parameter on other dependent variable is taken into consideration. A coefficient of determination named as R^2 which indicates the proportion of variance of dependent variable is used to measure the confidence of correlation. The same work was carried outin the past for the development of regression models by A. Ahmad, M. Adil, A. Khalil, M. Rahman [14] on concrete containing cardboard for determining its density and thermal conductivity. The value of R^2 for that regression model was developed greater than 0.95. A correlation developed by A. Meddah, M. Beddar, A. Bali [52] for strength loss of concrete pavement due to the increasing quantity of rubber content.

In this research study compressive strength and split tensile strength of concrete cylinders with uncoated and sand coated recycled plastics HDPE and recycled plastics were determined in order to know the improvement due to the effect of sand coating on strength properties of concrete. Compressive and split tensile strength are of prime interest for concrete samples and they are closely related to each other, but their correlation depends upon the natural strength of concrete. On the basis of results obtained on concrete with different replacement levels of plastics HDPE and E-wastes different regression models were developed and shown in Figures 21–24.

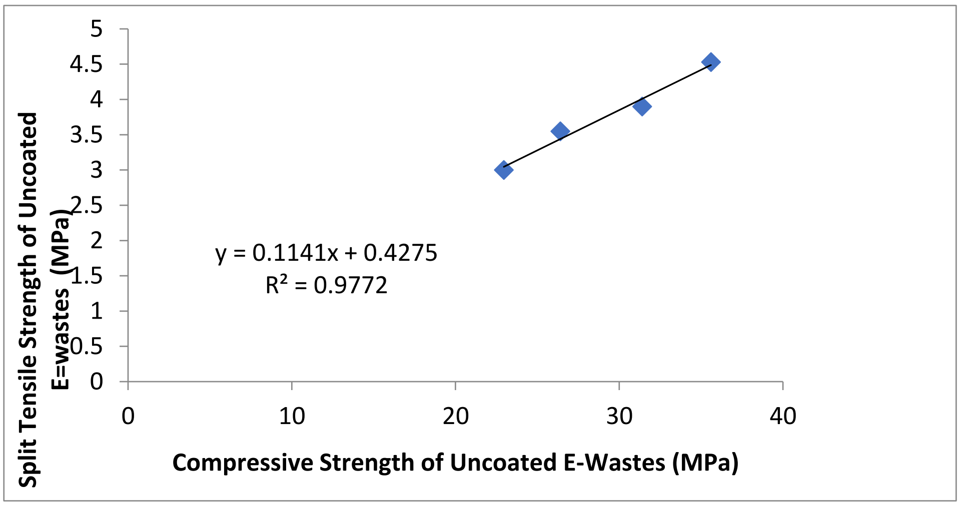

Figure 21. Correlation of compressive strength and split tensile strength of concrete with uncoated E-wastes.

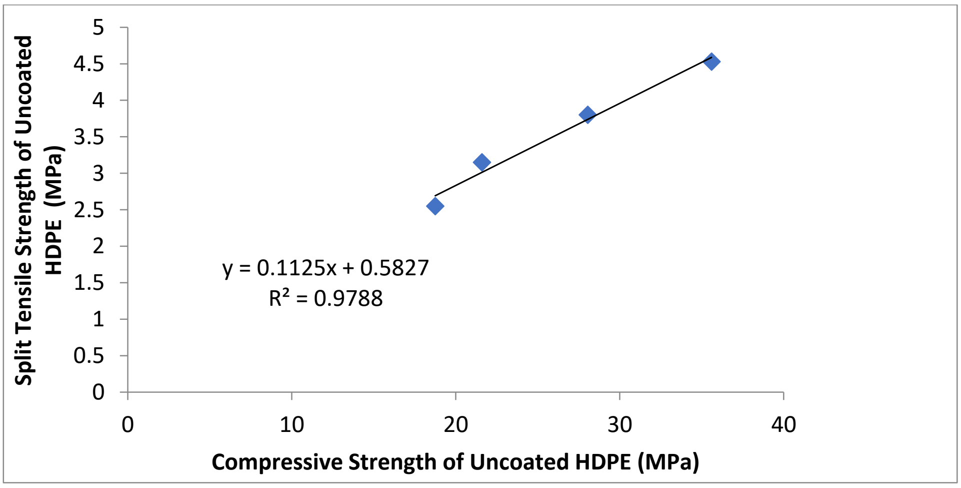

Figure 22. Correlation of compressive strength and split tensile strength of concrete with uncoated HDPE.

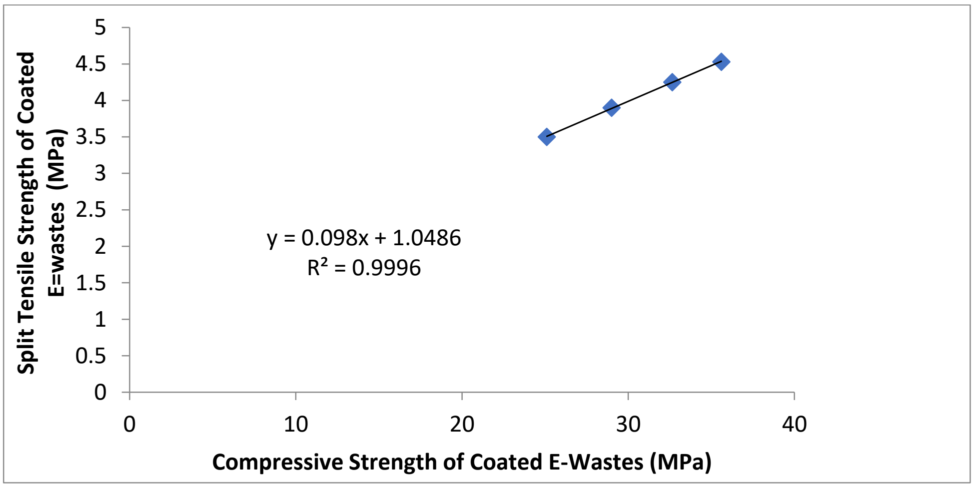

Figure 23. Correlation of compressive strength and split tensile strength of concrete with sand coated E-Wastes.

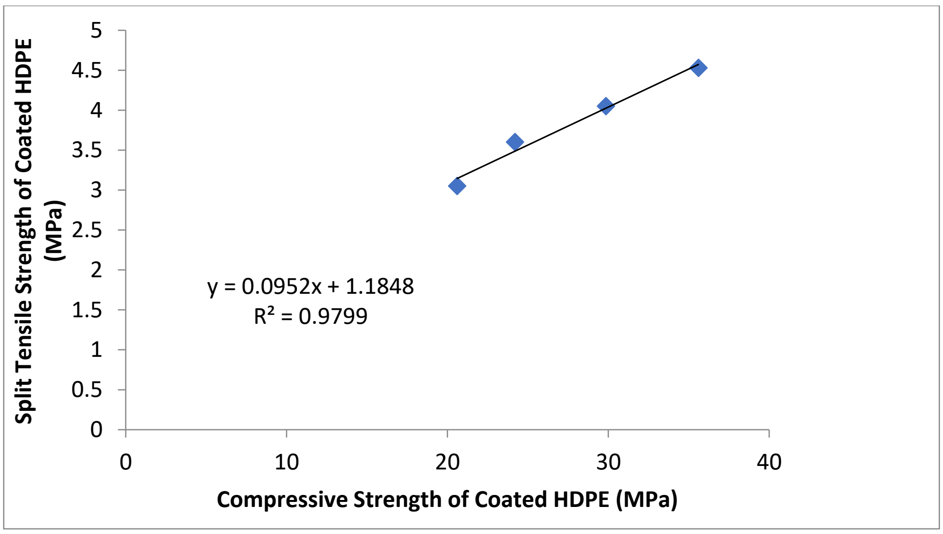

Figure 24. Correlation of compressive strength and split tensile strength of concrete with sand coated HDPE.

From Figure 21, a relation was developed between split tensile strength and compressive strength of concrete with uncoated E-wastes as shown in Equation (1). The value of R^2 = 0.977.

$$f_{sp} = 0.114(f_{cu}) + 0.427 \quad (1)$$

From Figure 22, a relation was developed between split tensile strength and compressive strength of concrete with uncoated HDPE as shown in Equation (2). The value of R^2 = 0.978.

$$f_{sp} = 0.112(f_{cu}) + 0.582 \quad (2)$$

From Figure 23, a relation was developed between split tensile strength and compressive strength of concrete with sand coated E-wastes as shown in Equation (3). The value of R^2 = 0.999.

$$f_{sp} = 0.098(f_{cu}) + 1.048 \quad (3)$$

From Figure 24, a relation was developed between split tensile strength and compressive strength of concrete with sand coated HDPE as shown in Equation (4). The value of R^2 = 0.979.

$$f_{sp} = 0.095(f_{cu}) + 1.184 \quad (4)$$

8. Conclusions and Recommendations

In this research study, we tried to incorporate two types of plastic wastes HDPE and E-wastes into the concrete to check their effect on the workability and mechanical properties of concrete. In addition to this, sand coating of both recycled plastics was carried out to improve bonding properties between cement paste and plastic aggregates. Another reason for using two types of plastics in concrete was to make a comparison and their effect on different properties of concrete. Following conclusions are drawn.

The workability of concrete with uncoated recycled plastics HDPE and E-wastes was found to be higher than concrete with sand coated HDPE and E-wastes. The decreased workability was attributed due to change in nature of recycled plastics from hydrophobic to hydrophilic and improved adhesion between cement paste and plastic aggregates. However, workability of concrete with E-wastes was found to be better as compared to concrete with HDPE.

There was an improvement in the compressive strength of concrete with sand-coated recycled plastic aggregates HDPE and E-wastes as compared to concrete with uncoated HDPE and E-wastes. The improved compressive strength values of concrete with sand coated recycled plastics HDPE and E-wastes were due to a change in the behavior of recycled plastics from hydrophobic to hydrophilic and better bonding between sand coated plastics and cement paste. The compressive strength values of concrete with E-wastes was found to be better than concrete with HDPE.

The split tensile strength of concrete with sand coated recycled plastics HDPE and E-wastes was also higher than concrete containing uncoated recycled plastics HDPE and E-wastes due to better bonding ability between cement paste and recycled plastics and change in nature of recycled plastics from hydrophobic to hydrophilic. The split tensile strength values of concrete with E-wastes was found to be better than concrete with HDPE.

Similarly, there was an improvement in the flexural strength property of concrete with sand-coated HDPE and E-wastes. Again, the reason was change in nature of HDPE from Hydrophobic to hydrophilic and improved bonding between cement paste and recycled plastics. From test results, it was concluded that the flexural strength values of concrete with E-wastes was found to be better than concrete with HDPE.

There was a significant effect of SP-675 on the slump of all concrete mixes with or without plastic aggregates. The recommended dose of SP-675 is 2% by weight of cement without compromising strength properties. A dose of SP-675 above 2% is not recommended for any type of concrete mix as it acts as a retarder. The use of admixture wet lock sealant in all concrete mixes showed some improvement in the strength properties of concrete.

The recommended dose of wet lock sealant in the concrete mix is 2 kg per bag of cement without compromising workability.

Different regression models for concrete with different replacement levels of recycled plastics HDPE and E-wastes were developed. All developed regression models are significant and levels of effectiveness of all regression models can be determined from values of R^2 which are in the range of 0.977 to 0.999.

The transformation from hydrophobic to hydrophilic behavior was the main reason for the improvement in strength properties of concrete samples due to sand deposition on the surface of recycled plastics named as HDPE and E-wastes since cement paste has a better bond with sand than recycled plastics. Adhesion between cement paste and recycled plastics became better due to presence of sand at the interface of recycled plastics and cement paste.

It is recommended that the durability of concrete containing uncoated and sand coated recycled plastic aggregates is further explored in future studies. In addition to this, micro test for sand coated recycled plastic aggregate concrete should be carried out in future research work as well.

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Abbreviations

NCA	Natural coarse aggregates
HDPE	High density Polyethylene
E-wastes	Electronic wastes
PET	Polyethylene Terephthalate (in Introduction paragraph)
SP-675	Super plasticizer 675

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