Producing Green Concrete with Plastic Waste and Nano Silica Sand

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Abstract-Industrial and urban development has resulted in the spread of plastic waste and the increase in the emissions of carbon dioxide resulting from the cement manufacturing process. The current research aims to produce green (environmentally friendly) concrete by using plastic waste as coarse aggregates in different proportions (10% and 20%) and nano silica sand powder as an alternative to cement in different proportions (5% and 10% by weight). The results showed that compressive strength decreased by 12.10% and 19.23% for 10% and 20% plastic waste replacement and increased by 12.89% and 20.39% for 5% and 10% silica sand replacement respectively at 28 days. Flexural strength decreased by 12.95% and 19.64% for 10% and 20% plastic waste replacement and increased by 11.16% and 19.86% for 5% and 10% silica sand replacement. Splitting tensile strength decreased by 12.74% and 20.22% for 10% and 20% plastic waste replacement and increased by 10.86% and 19.66% for 5% and 10% silica sand replacement. Dry density decreased by 4.51% and 7.83% for 10% and 20% plastic waste replacement and increased by 2.78% and 4.10% for 5% and 10% silica sand replacement respectively at 28 days.

Keywords-green concrete ; plastic waste; silica sand

I. INTRODUCTION

Green concrete was first produced in Denmark in 1998. The term green concrete refers to the environmental concept in which waste is utilized and thus recycled in its production. The production of green concrete is usually cheap because of the use of waste as a partial substitute for cement and aggregates, reducing energy consumption and causing less harm to the environment [1, 12, 13]. The emission of carbon dioxide (CO_2) is an environmental problem. The cement manufacturing process produces about 8 to 10% of the total CO_2 emissions globally, so researchers resorted to the production of green concrete, which utilized recycled materials, e.g. pozzolanic materials, which are used to reduce the amount of cement in the mixture, thus reducing cement production and CO_2 emissions from cement factories. Waste plastic, glass, ceramics, rubber, etc. have also been used as aggregates in the production of green concrete [2, 17]. The process of disposing of plastic waste causes major environmental problems due to the large disposed quantities and their low biodegradability, so research has focused on the disposal of plastic waste through its use in concrete [3, 14, 16]. Plastic waste consisting of Low-Density Polyethylene (LDPE), such as plastic bags, has become a major environmental problem due to the difficulty of its eco-friendly disposal. Often plastic bags are burned, contributing to air pollution [4, 15]. Green concrete developed with waste materials is an active area of research. Fly ash has been used as cement replacement in green concrete made with partial replacement of conventional coarse aggregates with coarse aggregates from demolishing waste [5]. Portland cement is considered a product most involved in environmental pollution. It is responsible for about 10% of global CO_2 emissions. Limestone dust is a by-product of limestone plants and it is produced in thousands of tons annually as waste [6]. For sustainable development construction, recycle or reuse of waste materials is utilized. Many researches tried to create an innovative green concrete, utilizing waste materials [7].

II. MATERIAL CHARACTERIZATION

A. Cement

Ordinary Portland Cement (OPC) 42.5 R from the Al-mass company was used in all concrete mixes. The physical and chemical properties in accordance with the Iraqi specification No. 5/2019 as shown in Tables I and II.

B. Fine Aggregates

Using natural sand in Saturated Surface Dry (SSD) condition was used as fine aggregates. It is conformable with the Iraqi specification No.45/1984 zone three (Tables III and IV).

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TABLE I. PHYSICAL PROPERTIES OF OPC

Physical properties	Test result	IQS No.5/2019 requirements for OPC
Fineness (Blaine method) m^2/Kg	386	≥ 280
Initial setting (min)	165	≥ 45 min
Final setting (min)	260	≤ 600 min
Soundness (autoclave method), %	0.12	≤ 0.8
Compressive strength (MPa) at 2 days	28	≥ 20
Compressive strength (MPa) at 28 days	46	≥ 42.5

TABLE II. CHEMICAL COMPOSITION AND MAIN COMPOUNDS OF THE CEMENT USED

Oxide composition and chemical properties	Test results	IQS No.5 /2019 limits for OPC
Lime (CaO)	62.77	-
Silica (SiO_2)	20. 65	-
Alumina (Al_2O_3)	4.87	-
Iron oxide (Fe_2O_3)	3.43	-
Magnesia (MgO)	4.35	$\leq 5\%$
Sulfate (SO_3)	2.50	$\leq 2.8\%$ for $C_3A > 3.5\%$
Loss on Ignition (L.O.I.)	1.36	$\leq 4\%$
Insoluble residue (I.R.)	0.91	$\leq 1.5\%$
Main Compounds (Bogue's equation)		
Tri calcium silicate (C_3S)	53.77	-
Di calcium silicate (C_2S)	18.72	-
Tri calcium aluminate (C_3A)	7.10	-
Tetra calcium aluminate - ferrite (C_4AF)	10.43	-

TABLE III. FINE AGGREGATE GRADING TEST

Sieve size (mm)	Passing%	IQS No.45/1984 zone 3 requirements
10	100	100
4.75	100	90– 100
2.36	93.8	85 – 100
1.18	80.8	75 – 100
0.6	61	60 – 79
0.3	21.8	12 – 40
0.15	1.8	0 – 10

TABLE IV. CHEMICAL AND PHYSICAL PROPERTIES OF FINE AGGREGATES

Property	Test result	IQS No.45/1984 requirements
Sulfate content, %	0.101	≤ 0.5
Fine materials Passing from 75μm sieve, %	3.9	≤ 5
Specific gravity	2.58	-
Fineness modulus, %	2.4	-
Dry rodded density, kg/m^3	1694	-
Absorption, %	0.8	-

C. Coarse Aggregates

Crushed gravel in SSD, of nominal maximum size of 14mm and conformable with the Iraqi specification No.45/1984 was used as coarse aggregates. Sieve analysis, and chemical and physical properties are shown in Tables V-VI respectively.

TABLE V. COARSE AGGREGATE GRADING TEST

Sieve size (mm)	Passing %	IQS No. 45/1984 5-14mm requirements
20	100	100
14	94	90 - 100
10	52.66	50 – 85
4.75	1.0	0-10

TABLE VI. CHEMICAL AND PHYSICAL PROPERTIES OF COARSE AGGREGATES

Property	Test result	IQS No .45/1984 requirements
Sulfate content as a SO_3, %	0.08	≤ 0.1
Specific gravity	2.62	-
Impact value, %	2.405	≤ 45
Abrasion test (Los Angeles), %	17.4	≤ 35
Crushing value, %	17.77	-
Dry rodded density, kg/m^3	1688	-
Absorption, %	0.7	-

D. Waste Plastic Aggregates

The plastic waste used as coarse aggregates had nominal maximum size of 14mm obtained from cutting vegetable boxes, garbage containers, shampoo, and detergent bottles. Sieve analysis, and the results of chemical and physical tests of the waste plastic aggregates are presented in Tables VII and VIII respectively.

TABLE VII. PLASTIC WASTE AGGREGATES GRADING TEST

Sieve size (mm)	Passing %	IQS No. 45/1984 5-14mm requirements
20	100	100
14	96	90-100
10	63	50-85
4.75	4.5	0-10

TABLE VIII. CHEMICAL AND PHYSICAL PROPERTIES OF PLASTIC WASTE AGGREGATES

Property	Test result	IQS No .45/1984 requirements
Sulfate content as a SO_3, %	Nile	≤ 0.1
Specific gravity	0.95	-
Impact value, %	0.00	≤ 45
Abrasion test (Los Angeles), %	0.00	≤ 35
Crushing value, %	0.00	-
Dry rodded density, kg/m^3	455	-
Absorption, %	0.00	-
Thickness, mm	Max3	-

E. Mixing and Curing

The water used for mixing and curing conforms to the Iraqi specification No. 1703/1992. The chemical properties of the water used are shown in Table IX.

TABLE IX. PROPERTIES OF THE WATER USED

Required tests	Test result	Iraqi specification No.1703/1992
Sulfur salts SO_3^{-2}, ppm	316	≤ 1000
Total Dissolved Salts (TDS), ppm	978	≤ 3000
Chlorides, ppm	118	≤ 500
Carbonate and bicarbonate, ppm	307	≤ 1000

F. High Range Water Reducing Admixture (Superplasticizer)

Hyperplastic PC200 complying with ASTM C494-04 type A and G was used in this research. The dosage recommended by the manufacturer is 0.5 - 2.5lt/100kg of cement weight in the mix.

G. Silica Sand Powder

Local silica sand was used in the form of powder. The particle size analysis test is presented in Figure 1. Chemical and physical tests for nano silica sand were carried out and were compared with ASTM C 618 as shown in Tables X and XI respectively.

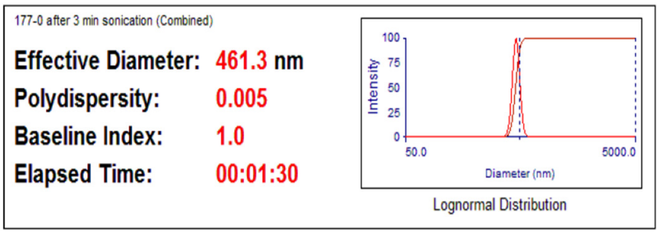

Fig. 1. Practical size analysis for silica sand powder.

TABLE X. CHEMICAL COMPOSITION OF NANO SILICA SAND POWDER

Property	Test result	Chemical requirements for Class N natural Pozzolan, ASTM C618-19
SiO_2 plus Al_2O_3 plus Fe_2O_3, %	90.04	70.0 Min.
SO_3, %	2.10	4.0 Max.
Loss on ignition, %	7.41	10.0 Max.
Moisture content, %	1.8	3.0 Max
Calcium oxide (CaO), %	4.66	-
Magnesium oxide (MgO), %	1.23	-

TABLE XI. PHYSICAL PROPERTIES OF NANO SILICA SAND POWDER

Property	Test result	Physical requirements for Class N natural Pozzolan, ASTM C618-19
Amount retained when wet sieved on 45 µm, %	0	34 Max.
Strength activity index with Portland cement at 7 days, percentage of control	87.46	75 Min.
Strength activity index with Portland cement at 28 days, percentage of control	92.54	75 Min.

III. EXPERIMENTAL PART

A. Mixtures

ACI 211.1 code design was used to achieve compressive strength of 30MPa at 28 days for cylinder and 37.5MPa for cube specimens as the reference mix. The plastic waste was replaced in different proportions of the volume of the coarse aggregates (natural gravel), and the silica sand replaced cement in different proportions as shown in Table XII.

B. Molds Preparation

Cube steel molds having dimensions of 100×100×100mm were utilized for compressive strength tests, cylinder steel molds of 100×200mm for splitting tensile strength tests, and 100×100×400mm prisms for flexural strength tests.

TABLE XII. MATERIAL CONTENT FOR THE DESIGNED CONCRETE

Materials kg/m^3	Ref.	10% PL*	20% PL	5% SS**	10% SS
Cement	400	400	400	380	360
Fine aggregates	727	727	727	727	727
Coarse aggregates	1020	918	815	1020	1020
Plastic waste	0	27.5	55	0	0
Silica sand	0	0	0	20	40
Water	171	171	171	171	171
S.P. L/100Kg cement	0.75	0.75	0.75	0.80	0.85

*PL: Plastic coarse aggregates, **SS: Silica Sand

IV. RESULTS AND DISCUSSION

A. Compressive Strength Measurements

Compressive strength test was conducted according to BS EN 12390-3:2019 (E) as shown in Figure 2. The compressive strength was tested for three cubes at the age of 7, 28, and 90 days.

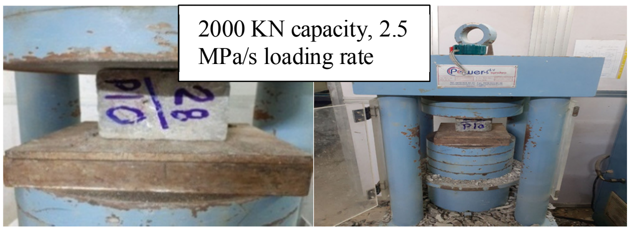

Fig. 2. Compressive strength test machine.

The results for the reference mix and the concrete containing plastic aggregates are plotted in Figure 3. It was found that the compressive strength decreased by 10.84, 12.10, and 13.62% and by 18.18, 19.23, and 20.15% for 10% and 20% plastic waste replacement, respectively, at 7, 28, and 90 days. A possible reason for the decrease in the compressive strength is the weakness of the bonding strength between the smooth surface of the plastic aggregates and the cement paste, which leads to a weakening of the transition zone [21-23]. Plastic waste (high density polyethylene) in concrete mixtures as aggregate replacement was studied in [8]. The authors used plastic waste in the concrete mixture with proportions of 10, 20, and 30% of the volume of coarse aggregates. The compressive strength decreased with increasing plastic waste proportion [8].

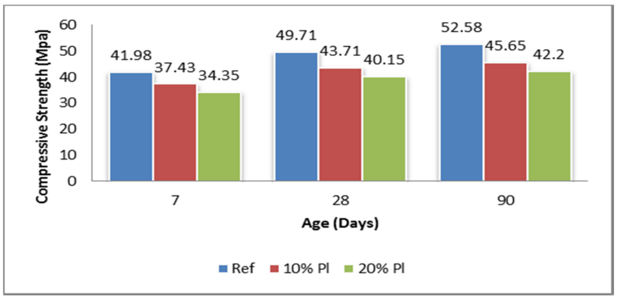

Fig. 3. Relationship between compressive strength and age for deferent percentages of plastic waste as coarse aggregates.

The compressive strength test results for the reference mix and the concrete containing the silica sand powder are plotted in Figure 4. The compressive strength increased by 10.20, 12.89, and 12.64% and by 19.46, 20.39, and 19.11% for 5% and 10% silica sand replacement, respectively, at 7, 28, and 90 days. The reason for the increase in compressive strength is the reaction of calcium hydroxide ($Ca(OH)_2$), which is a product of the reaction of cement and water with silica sand, which leads to the formation of a secondary gel (C-S-H) [20]. The mechanical properties of concrete using silica sand as partial (5, 10, 15, 20 and 25% by weight) replacement of cement were studied in [9]. It was found that the best replacement ratio was 15% [9].

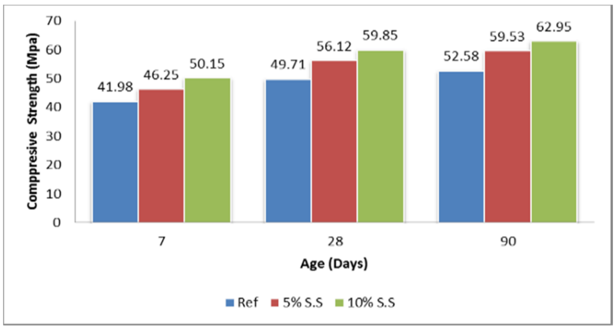

Fig. 4. Relationship between compressive strength and age for deferent percentages of silica sand powder.

B. Flexural Strength

Flexural strength was determined according to ASTM C293-16 as shown in Figure 5. The flexural strength average of three models per mixture was examined at the age of 7, 28, and 90 days.

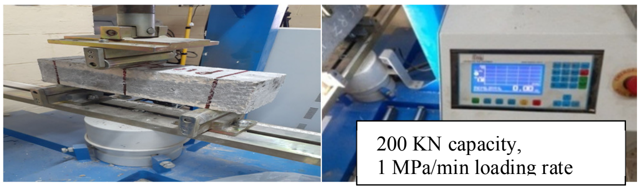

Fig. 5. Flexural strength test machine.

The results of the flexural strength measurements for the reference mix and the concrete containing plastic aggregates are plotted in Figure 6. Flexural strength decreased by 12.26, 12.95, and 10.81% and by 21.63, 19.64 and 19.10% for 10% and 20% plastic waste replacement, respectively, at 7, 28, and 90 days. The reason is the same with the one mentioned in compressive strength analysis [24]. Some properties of sustainable concrete with mixed plastic waste aggregates can be seen in [10]. When replacing aggregates with plastic waste at proportions of 5, 25, and 45% of volume, a decrease in flexural strength was observed with an increase in the replacement ratio. The flexural strength test results for the reference mix and the concrete containing the silica sand powder are plotted in Figure 7. Flexural strength increased by 11.1, 11.16, and 11.6% and by 17.78, 19.86, and 18.64% for 5% and 10% of silica sand replacement, respectively, at 7, 28, and 90 days. The reason is the one mentioned in compressive strength analysis [9, 19]. The use of silica sand in partial replacement of the fine material (sand) in concrete was studied in [20]. The best replacement ratio was found to be 15% [20].

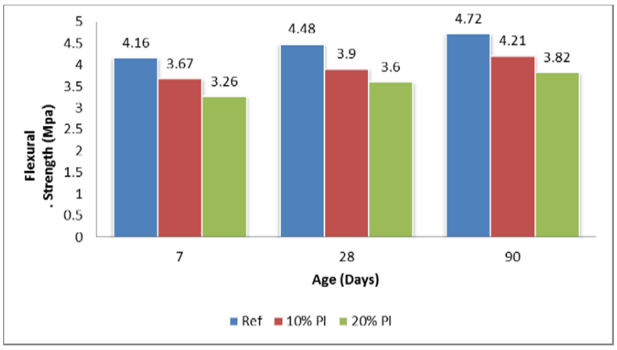

Fig. 6. Relationship between flexural strength and age for deferent percentages of plastic waste as coarse aggregates.

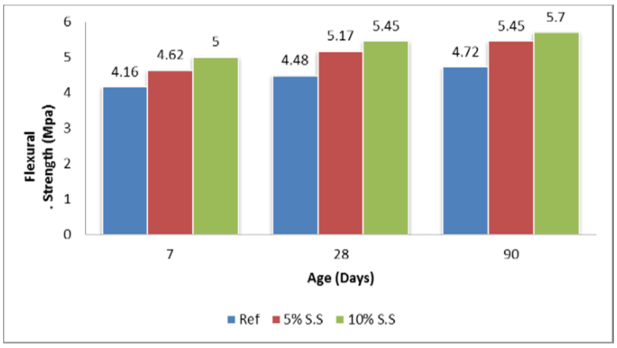

Fig. 7. Relationship between flexural strength and age for deferent percentages of silica sand powder.

C. Splitting Tensile Strength

Splitting tensile strength test was determined according to ASTM C496/C496M-17 at the age of 7, 28, and 90 days (Figure 8). The average of three measurements was considered the final value of each mixture.

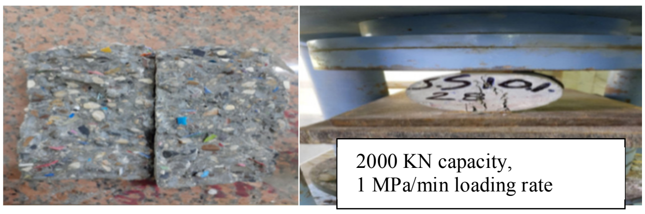

Fig. 8. Splitting tensile strength test.

The results of the splitting tensile strength tests for the reference mix and the mixtures containing plastic aggregates are plotted in Figure 9. Splitting tensile strength decreased by 11.77, 12.74, and 13.76% and 19.34, 20.22, and 20.63% for 10% and 20% of plastic waste replacement, respectively, at 7, 28, and 90 days. The reason is the same mentioned in compressive strength analysis [10, 25]. The use of plastic waste (high density polyethylene) in concrete mixture as aggregate replacement was studied in [8]. Plastic waste was utilized in concrete mixtures with proportions of 10, 20, and 30% of the volume of coarse aggregates. It was found that splitting tensile strength decreased by increasing percentage of plastic waste [8]. Splitting tensile strength for the reference mix and the concrete containing silica sand powder is plotted in Figure 10. Splitting tensile strength increased by 10.71, 10.86, and 11.37% and by 17.60, 19.66, and 18.50% for 5% and 10% of silica sand replacement, respectively, at 7, 28, and 90 days. The reason mentioned in compressive strength analysis [9, 18] also applies here. The use of silica sand as partial replacement of fine materials in concrete was studied in [20]. The best replacement ratio was proved to be 15% of cement weight [20].

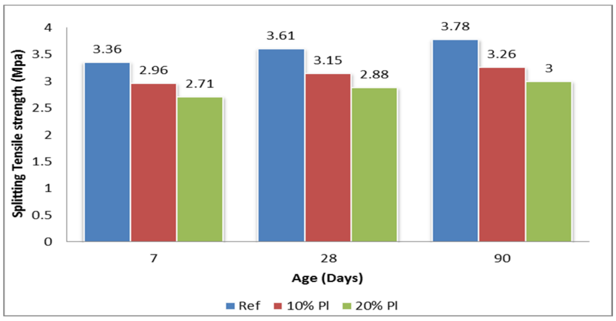

Fig. 9. Relationship between splitting tensile strength and age for deferent percentages of plastic waste as coarse aggregates.

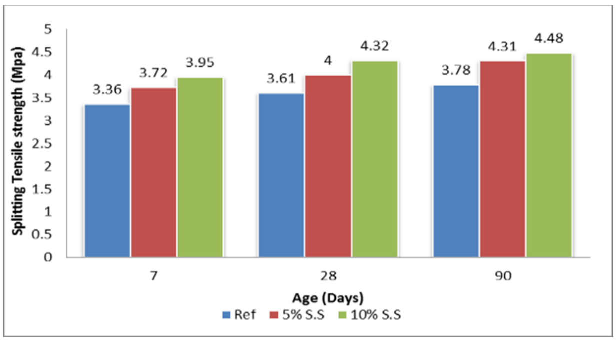

Fig. 10. Relationship between splitting tensile strength and age for deferent percentages of silica sand powder.

D. Dry Density

Dry density test was found by taking the average density of three cubs of 100×100×*100 dimensions at the age of 28 days according to BS 1881-114: 1983. The cubes were drying in the oven at 105 ± 5 ℃ until constant mass. Dry density decreased by 4.51% and 7.83% for 10% and 20% plastic waste replacement, respectively, at 28 days. This decrease in the dry density of concrete is caused by the decrease in the plastic density compared to the density of the natural coarse aggregate [26-28]. Experimental investigation on recycled plastics as aggregates in concrete was conducted in [11]. It was found that dry density decreased with increasing plastic waste percentage [11].

Silica sand powder was utilized at proportions of 5% and 10%. It was found that the density of dry concrete increases by 2.78% and 4.10% respectively at 28 days. The reaction of calcium hydroxide $Ca(OH)_2$ with silica sand powder leads to the formation of a secondary gel (C-S-H) that fills the voids in concrete, making the mixture more denser [9]. The effect of nanomaterials on the properties of limestone dust green concrete was studied in [6]. It was found that dry density increased with the increase in nano Al_2O_3 percentage [6]. The dry density for the reference mix and the concrete containing plastic and silica sand powder are plotted in Figure 11

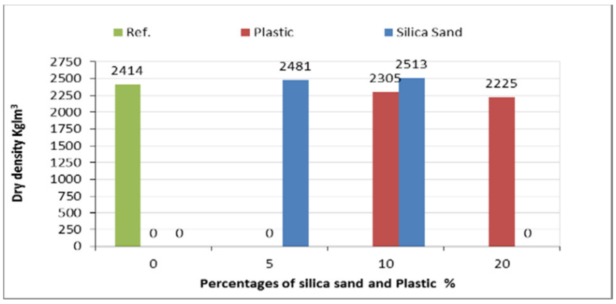

Fig. 11. Relationship between dry density and deferent percentages of plastic waste and silica sand powder .

V. CONCLUSIONS

Based on the obtained experimental results, the most notable outcomes of the current study are:

- Compressive strength decreased by 10.84, 12.10, and 13.62% and by 18.18, 19.23, and 20.15% for 10% and 20% plastic waste replacement, and increased by 10.20, 12.89, and 12.64% and 19.46, 20.39, and 19.11% for 5% and 10% silica sand replacement, respectively, at 7, 28, and 90 days.
- Flexural strength decreased by 12.26, 12.95, and 10.81% and 21.63, 19.64, and 19.10% for 10% and 20% plastic waste replacement, and increased by 11.1, 11.16, and 11.6% and 17.78, 19.86, and 18.64% for 5% and 10% silica sand replacement, respectively, at 7, 28, and 90 days.
- Splitting tensile strength decreased by 11.77, 12.74, and 13.76% and 19.34, 20.22, and 20.63% for 10% and 20% plastic waste replacement and increased by 10.71, 10.86, and 11.37% and 17.60, 19.66 and 18.50% for 5% and 10% silica sand replacement, at 7, 28, and 90 days respectively.
- Dry density decreased by 4.51% and 7.83% for 10% and 20% plastic waste replacement, respectively, at 28 days. It increased by 2.78% and 4.10% for 5% and 10% silica sand replacement, respectively, at 28 days.
- The cost of concrete was reduced by using local and recycled materials.
- The concrete production had reduced pollution by using plastic waste as coarse aggregates.

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