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Mechanical and physical properties of eco-friendly recycled plastic concrete (RPC)

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ABSTRACT

In this research, an Eco-friendly **R**ecycled **P**lastic **C**oncrete (RPC) having good workability, low density, thermal isolation characteristics, and can be used in structural applications has been engineered. One reference mixture in addition to nine RPC mixtures were studied, where the plastic granules were used as a partial replacement of sand and/or gravel by volume. The studied parameters were the replacement ratios of fine and coarse aggregates by plastic granules; the replacement ratios were: 1) 100, 80, and 60 % from sand; 2) 50, 40, and 30 % from gravel; and 3) 100, 80, and 60 % from sand simultaneous with 30 % from gravel. The effect of incorporating plastic on the physical, mechanical, and thermal properties of the newly developed RPC mixtures have been investigated experimentally via thirty concrete standard cubes (150 × 150 × 150 mm), thirty concrete standard cylinders (150 × 300 mm), and 30 S-shape prisms. A statistical analysis on the test results was carried out using commercial software to determine the optimum proportions of the studied RPC mixtures. The criteria were to maximize the required strengths and to minimize the required density and thermal conductivity. The conducted optimum sand/gravel replacement ratios were 30 % for sand and 80 % for gravel, which were similar to the replacement ratios of Mixture 8 in the current research. This optimum mixture has a unit weight of 1900 kg/m^3 and a compressive strength of 27.7 MPa, which were found to meet the limits of structural light weight concrete according to ACI 213R-14 and supports both structural and environmental benefits.

1. Introduction

Due to its importance in the construction industry, concrete is considered the second most consumed material in the world after water [1,2]. To serve the environment, the general trend in the research society has now become to study the effect of the replacement of the natural aggregates in concrete with other recycled materials such as plastic, leftover tires, and building demolition products to get rid of the waste materials. From here, the concept of environmentally friendly concrete emerged. A considerable amount of plastic waste has been generated because of the rise in plastic usage. About 300 million tons of plastic waste are produced worldwide each year [3,4]. Common polymers with short lives, such as polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC), make up as much as 45 % of plastic garbage [5]. Nowadays, there are three primary ways to get rid of plastic waste: recycling, landfilling, and incineration. Air pollution can result from harmful gases like dioxins from the incineration of plastic waste. Placing plastic waste in a landfill takes up a lot of space and can clog drainage systems, which leads to mosquitoes and spreads illness [6]. Plastic waste, comprising 85 % of marine debris, is the most prevalent, dangerous, and urgent waste type, with 4–12 million tons

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discarded annually into the ocean [7,8].

Recycling waste plastics is the best solution for reducing economic, environmental, and public health impacts, but its high impurity level limits its use. Only 9 % of 8.3 billion tons of plastic products were recycled in 2015; the rest were burned, buried, or thrown away [9]. Only 15–18 % of plastic was predicted to be recycled by 2022 [10]. In the construction field, concrete is the material that is used the most [11–13]. The demand for aggregates for building and infrastructure projects is expected to increase by 2.4 % per year to 46.3 billion metric tons in 2023 as a result of a continuing increase in building activity worldwide [14–17]. Because of the decreasing amount of natural building materials and the anticipated need for construction, it is essential to develop alternative materials for natural aggregates [18–20]. By using recycled plastic instead of natural aggregates in the concrete industry, concrete would be an advantageous building material for the environment [21,22]. In addition, one of the advantages of using plastic in the concrete industry is the potential of producing light self-weight concrete. Plastic materials have been widely used in concrete mixtures as a replacement material for different applications over the past few years [23–30].

Recently, research work has been concerning the use of recycled plastic waste in concrete. For example, Albano et al. [27] studied the mechanical behavior of concrete with recycled Polyethylene Terephthalate (PET). The findings showed that compressive strength, splitting tensile strength, modulus of elasticity, and ultrasonic pulse reduced with an increase in PET portion and particle size. Waste PET particles were added by Safi et al. [28] to replace sand for mixing self-compacting mortar. Increasing the amount of plastic seemed to decrease the compressive strength. Belmokaddem et al. [29] studied the effect of replacing fine and coarse aggregates with three different plastic wastes with different amounts of natural aggregates. The findings demonstrated that using plastic waste improved thermal characteristics; however, using plastic waste caused the compressive strength to systematically decrease as the amount of recycled plastic aggregate increased. Earlier studies [31,32] described experimental testing on concrete containing coarse or fine aggregate that had a portion of its fine aggregate replaced with plastic waste from PVC waste sheets. The findings indicated that, when the PVC aggregate replacement ratio exceeded 30 %, the developed concrete would not have good workability. The possibility of using waste plastic in place of natural aggregates in concrete was investigated by Basha et al. [33]. High-strength self-consolidating concrete (SCC) made of recycled polypropylene plastic particles, both with and without silica fume, was investigated by Faraj et al. [34]. The mechanical characteristics of concrete that replaced natural aggregates with three different types of recycled PET were investigated by Saikia and Brito [35]. The researchers reached the conclusion that plastic concrete's mechanical properties were not as good as those of conventional concrete [33–35].

Also, using recycled plastic has a remarkable advantage in improving the thermal properties of the **R**ecycled **P**lastic **C**oncrete (RPC) mixtures owing to the low thermal conductivity of the plastic if compared with sand and gravel. This will help to improve the efficiency of energy consumption and isolation of the constructions built using RPC. Many research works have studied the effect of using the plastic/rubber compositions in the new types of concrete on the thermal properties [36–38]. M. Záleská et al. [39] studied the thermal conductivity of concrete mixtures containing three different types of plastic waste substituting up to fifty percent of natural aggregates. The findings showed that, as the polypropylene (PP) aggregate content increased, the thermal conductivity rapidly dropped in comparison to the reference mixture. Additionally, S.I. Basha et al. [33] investigated three distinct types of recycled plastic at differing amounts to evaluate their mechanical and physical qualities. The findings demonstrated that when the quantity of recycled plastic aggregates (RPA) increased, the thermal conductivity dropped. While the thermal conductivity of RPA combinations ranged from 1.1 to 0.5 W/mK, the thermal conductivity of the control mixture was 1.7 W/mK.

Although there are numerous benefits of replacing plastic instead of natural aggregates in the concrete, there are also many drawbacks that should be considered. Using some types of plastics in the concrete industry with non-uniform shapes and large sizes leads to low-workability concrete [31,32]. Plastic replacement has a high potential to produce concrete that has a weak compressive strength, suitable only for non-structural purposes [27,35]. Many types of concrete incorporating plastic are expected to have weak aggregate interlocking and, accordingly, weak shear strength. However, it was noticed that most of the previous studies did not assess the effect of plastic replacement on the shear strength of the developed concrete [29,33]. In this research, a newly developed type of eco-friendly recycled plastic concrete (RPC) was engineered to serve both environmental and structural benefits. This RPC is planned to have good workability, light weight, thermal isolation characteristics, and appropriate compressive strength that can be employed in several structural applications. To reach this goal, one reference mixture and nine RPC mixtures having several plastic replacement ratios from sand and/or gravel were experimentally investigated. The shear strength, compressive strength, physical properties, and thermal characteristics were studied. Subsequently, a statistical analysis on the test results was carried out to determine the optimum RPC mixture.

2. Experimental work

2.1. Materials

The engineered concrete in this research was planned to be utilized in structural applications; therefore, a high cement grade of 52.5 was used to compensate for the potential reduction in the compressive strength due to aggregate replacement. The used cement type complied with EN 197-1 [40]. Silica-fume was used to improve the mixture properties, such as compressive strength, bond strength, and abrasion resistance, because of its extreme fineness and high silica content [34]. The used fine aggregate was medium-well-graded quartz sand with a fineness modulus of 2.47, a specific gravity of 2.65, a unit weight of 1650 kg/m^3, and water absorption of 0.65 %. Dolomite aggregate with a size of 2 cm was used as coarse aggregate, and its specific gravity is 2.60, its unit weight is 1650 kg/m^3, and its water absorption ratio is 1.98 %. Acrylonitrile butadiene styrene plastic (Abs) was studied to replace a portion of fine or coarse aggregates by volume, as shown in Fig. 1. Abs plastic has a specific gravity of 1.00 and a unit weight of 602 kg/m^3. The used admixture was Sika ViscoCrete-3425 as a superplasticizer to increase both the workability as well as concrete

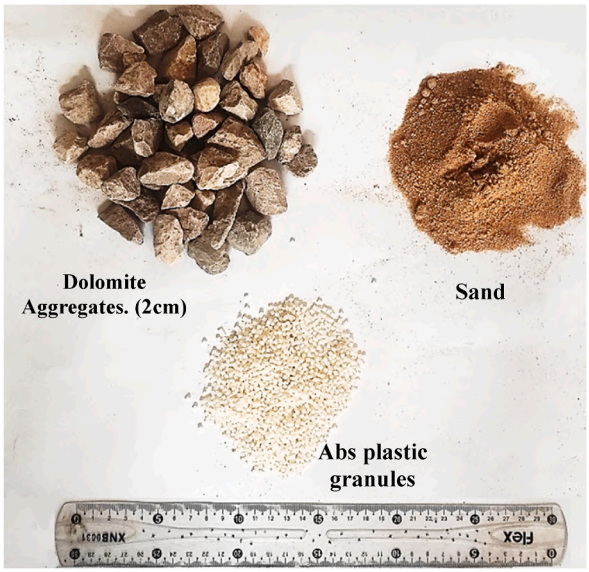
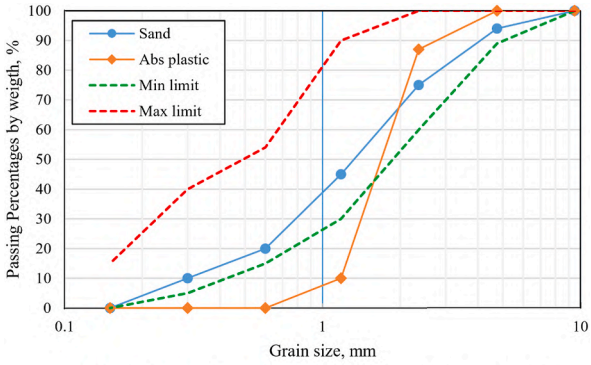
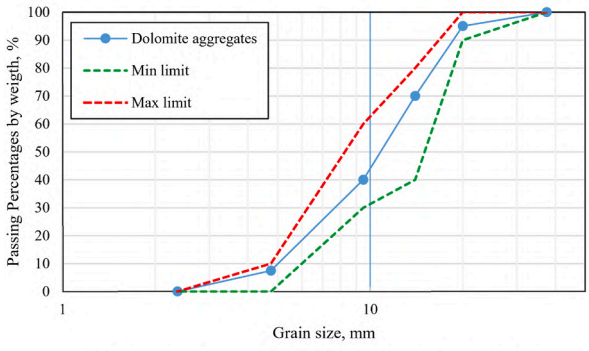


Fig. 1. The used Abs plastic granules and natural aggregates.



(a) Grain size distribution of sand and Abs plastic granules vs. EN 812-2 limits [41].



(b) Grain size distribution of dolomite aggregates vs. EN 812-2 limits [41].

Fig. 2. Grain size distribution of the used sand, Abs plastic granules, and Dolomite aggregates.

compressive strength. According to the technical data sheet, Sika ViscoCrete-3425 has a density of 1.08 kg/L, a pH value of 4.0, and a solid content of 40 % by weight. The grain size analysis was carried out for the used Abs plastic granules and natural aggregates according to EN 812-2 [41], which describes the maximum and minimum permissible limits for passing percentages by weight for fine and coarse aggregates at each sieve size. It was observed that most amounts of plastic granules are between two sieves of different sizes) 0.6 and 2.36 mm), so plastic granules can be classified as fine aggregates. Fig. 2 shows the grain size distribution of Abs plastic and natural aggregates vs. the limits of EN 812-2 [41] for fine and coarse aggregates, separately.

Table 1
The plastic granules replacement ratios from natural aggregates.

Group NO.	Mix ID	Volumetric Replacement Ratio %	
		Sand	Gravel
G0	Mix A (Reference mixture)	0 %	0 %
G1	Mix 1	100 %	0 %
	Mix 2	80 %	0 %
	Mix 3	60 %	0 %
G2	Mix 4	0 %	50 %
	Mix 5	0 %	40 %
	Mix 6	0 %	30 %
G3	Mix 7	100 %	30 %
	Mix 8	80 %	30 %
	Mix 9	60 %	30 %

Table 2
Mix ingredients of RPC mixtures, kg/m.^{3}.

Group NO.	Mix ID	Mix proportions, kg/m^3				
		Cement	Silica-Fume	Sand	Gravel	Abs granules
G0	Mix A (Reference mixture)	427.5	22.5	704	1056	0
G1	Mix 1			0	1056	265
	Mix 2			141	1056	212
	Mix 3			282	1056	159
G2	Mix 4			704	528	199
	Mix 5			704	633	159
	Mix 6			704	740	120
G3	Mix 7			0	740	385
	Mix 8			141	740	331
	Mix 9			282	740	278

Where; Abs is Acrylonitrile butadiene styrene plastic.

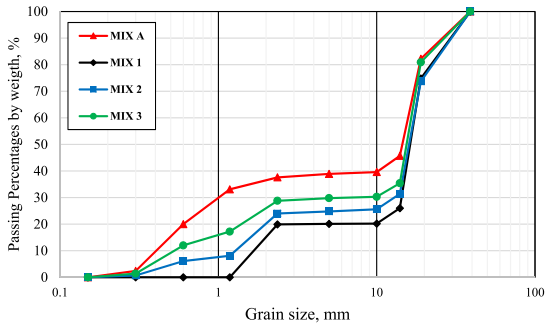


Fig. 3. All-in aggregate grain size distribution of control mixture and Group (1).

2.2. Mixtures proportions

In this study, ten concrete mixtures were designed according to EN 206-1 [42]. The mixtures were designed so that portions of the coarse and/or fine aggregates were replaced using plastic granules while maintaining constant volume of the mixture, which may lead, in some cases, to reduce the density of the mixture. As the percentage of sand in the mixture is almost half the percentage of gravel, and since gravel is important in aggregate interlocking, which plays a major role in shear resistance. Therefore, the percentage chosen for plastic replacement for sand was selected twice as the percentage of plastic replacement for gravel. The mixtures were classified into four groups: The first group (G0) has an individual reference mixture (Mix A), which does not contain any percentage of plastic replacement. The second group (G1) consists of three mixtures (Mix 1, Mix 2, and Mix 3) having three different percentages of plastic replacement ratios instead of sand only (100, 80, and 60 %), respectively. The third group (G2) consists of three mixtures (Mix 4, Mix 5, and Mix 6) with three different percentages of plastic replacement ratios instead of coarse aggregates only (50, 40, and 30 %), respectively. The fourth group (G3) consists of three mixtures (Mix 7, Mix 8, and Mix 9) at which three different plastic ratios were replaced simultaneously from both coarse and fine aggregates. The simultaneous replacement ratios were as follows: from sand (100, 80, and 60 %) and 30 % from gravel for all mixtures as shown in Table 1. The ingredients of the studied mixtures are listed in Table 2.

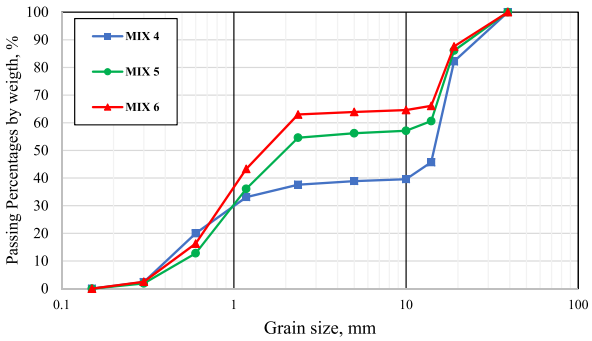


Fig. 4. All-in aggregate grain size distribution of Group (2).

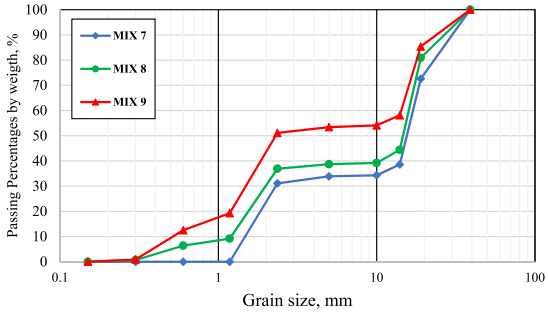


Fig. 5. All-in aggregate grain size distribution of Group (3).

Table 3
The permissible limits of all-in aggregate percentage passing as per EN 812-2 [41].

Sieve opening, mm	20	14	10	5	2.36	1.18	0.6	0.03	0.015
Percentage passing %, Maximum normal size, 20 mm	95–100	–	–	35–55	–	–	10–35	–	0–8

For all mixtures, the binder content (cement and silica-fume) was 450 kg per cubic meter; therefore, the cement content was 427.5 kg/m^3 and the silica-fume content was 22.5 kg/m^3. The water to binder ratio was constant for all mixtures and equal to 0.4. For the reference mixture (MixA), the specified amount of fine aggregate as a volume of total aggregate was 40 % to obtain a good granular gradation. The dose of Super-Plasticizer was 0.26 % liter by weight of blinder, which coincides with the technical sheet of the manufacture. Grain size analysis was carried out to determine the all-in aggregate grain size distribution of RPC mixtures according to EN 812-2 [41] (The mixture of sand, gravel, and Abs plastic granules). The results of passing percentage vs. sieve opening sizes were plotted in Figs. 3–5. The permissible limits of all-in aggregate percentage passing according to EN 812-2 [41] are summarized in Table 3. It was obvious that mixtures A, 6, 8, and 9 are only the mixtures having ingredients within the permissible limits.

2.3. Tests procedures

2.3.1. Fresh properties

Following mixing, the ASTM C143 [43] slump test was performed to measure the fresh concrete's workability and assess how the plastic granules affected the fresh properties of the new RPC. All slump tests were conducted in the lab at 25 ± 3 °C and 60 ± 5 % relative humidity.

2.3.2. Hardened properties

Following the curing period, the samples were de-molded, and the unit weight was calculated in a dry condition in accordance with EN 12390-7 [44] to assess the impact of replacing sand and gravel with plastic granules. Using micrometric instruments (**Autopore III**), mercury intrusion porosimetry was used to assess the open porosity [36]. The water absorption of RPC mixtures was calculated according to ASTM C127-01 [45]. To estimate the compressive strength at 28 days, thirty concrete standard cubes (150 × 150 × 150 mm) and thirty concrete standard cylinders (150 × 300 mm) were sampled (three samples for each mixture). The shear friction strength at 28 days was determined via push-off test using 30 S-shape prisms (three samples for each mixture).

2.3.2.1. Push-off test. Shear failure is among the most critical topics in reinforced concrete structures due to specific characteristics

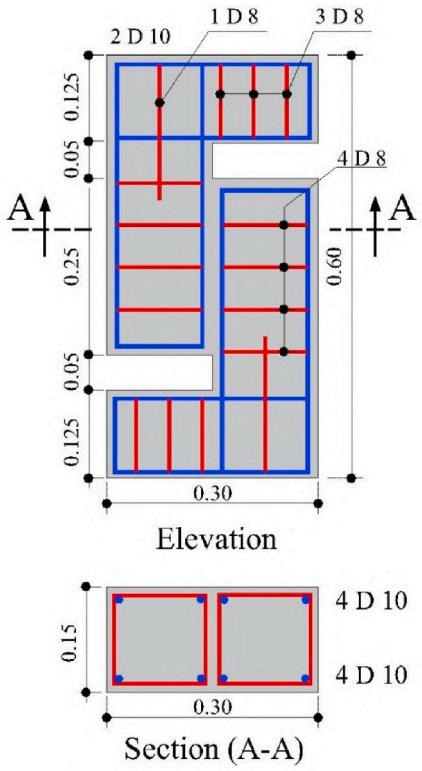


Fig. 6. Configuration of the tested S-shape prism.

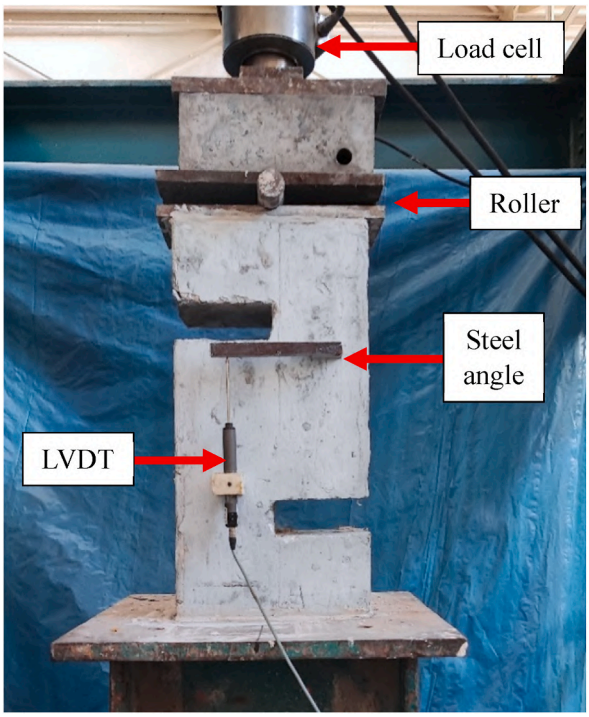
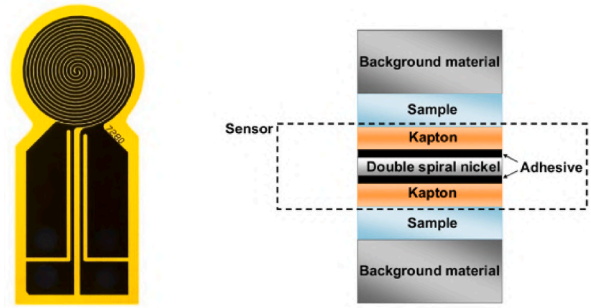


Fig. 7. Push-off test setup and instrumentation.



(a) TPS double spiral ring sensor

(b) Cross section at TPS sensor and tested sample

Fig. 8. Transient plane source sensor.



Fig. 9. RPC cylinder sample for TPS test.

that shear failure owns, including no signs of warning and a brittle nature. The push-off test was performed to calculate shear friction strength and to investigate the shear performance of the developed RPC mixtures. The push-off test is non-standard, inexpensive, and easy to perform with no need for any specialized equipment to carry out [46]. In the current research, the dimensions and the test instrumentation were selected as per the previous research works [47–51]. The dimensions of specimens and reinforcement configuration were shown in Fig. 6. To avoid crushing the concrete away from the specified shear plane, the s-shape specimens were reinforced by steel bars with 8 and 10 mm diameter. Across the shear plane, load and deformation were monitored during the test. The deformation was recorded by a linear variable differential transformer (LVDT). The typical configuration of the test is shown in Fig. 7. The test was carried out using a displacement-controlled system with a loading rate of 0.05 mm/min until failure. The specimens were put on a steel pedestal rested on the testing frame. The rollers were used to ensure that separation of the two halves of the s-shape prisms was not restrained by the testing machine. A vertical notch with a depth of 5 mm was executed to ensure that the collapse surface is uniform.

2.3.3. Thermal properties of the RPC mixtures

Building energy usage for heating and cooling is significantly impacted by the quantity of heat lost via walls and roofs. The following variables have an impact on the thermal characteristics of concrete: temperature, moisture content, type of aggregate, type of cementitious material, and density [52–55]. The thermal characteristics assessed in the current study are thermal conductivity (k-value), thermal diffusivity, and specific heat. The ability of a material to conduct heat is known as its thermal conductivity, the rate at which heat transfers from a material's hot to cold ends is measured by its thermal diffusivity, and the specific heat is the quantity of heat energy required to change an object's temperature by one unit [54]. The steady state and transient methods are considered the two main thermal measurement approaches [54]. Also commonly known as the "hot disk method", the transient plane source (TPS) methodology has gained widespread acceptance as a suitable and quick way to evaluate the thermal characteristics of materials with thermal storage. Materials' through-plane and in-plane thermal conductivity are measured using the TPS method. One of the main advantages of the TPS method is that the influence of the contact resistance in the analysis of experimental data is avoided; therefore, accurate records are provided [56].

This method uses a sensor that has a form of multiple rings (double spiral) as shown in Fig. 8-a that acts as a planar heater for increasing the temperature of the sample besides acting as an Ohmic resistance thermometer for recording the increase of time-dependent temperature. As illustrated in Fig. 8-b, these spirals are made of nickel and are easily inserted between the two parts of the evaluated sample. They are covered on both sides with Kapton for electrical insulation and protection. A tiny, steady electric current is applied during the test, and the voltage the sensor produces is proportionate to the temperature. The TPS sensor 7577 with a radius of 2.1 mm was inserted between two identical uniform dicks of the same material. Two 20 mm thick slices were cut from the center of the 50 mm diameter and 100 mm height of the RPC cylinder to be examined by this method, as indicated in Fig. 9. The specimen sampling was done in accordance with previous studies [53,56]. To ensure optimal contact with the sensor, a very thin layer

Table 4
Densities, compressive, and shear strengths of the RPC mixtures at 28 days.

Mix ID	Samples	Density, kg/m^3	A %	Open porosity %	Slump, mm	Compressive strength for cubes, MPa			Compressive strength for cylinders, MPa			Shear strength for S-shape primes, MPa		
						f_{cu}	Mean value	U_{exp}	f_c‘	Mean value	U_{exp}	ν	Mean value	Δ, mm
Mix A	1-A	2330	8.1	18.0	120	53.6	55.9	±2.42	42.7	42.9	±1.49	4.7	4.6	0.175
	2-A					57.5			41.9			4.6		0.168
	3-A					56.5			44.2			4.6		0.169
Mix 1	1-a	1913	11.5	23.1	90	20.5	26.3	±7.43	19.5	23.0	±5.36	2.1	2.5	0.077
	1-b					33.2			28.2			2.5		0.067
	1-c					25.3			21.2			3		0.101
Mix 2	2-a	2030	11.0	22.5	95	42.5	42.6	±1.27	32.2	33.7	±1.79	2.8	3.0	0.107
	2-b					43.6			35.1			3.1		0.120
	2-c					41.7			33.7			3.2		0.109
Mix 3	3-a	2107	10.8	21.5	110	43.9	43.2	±2.02	39.7	36.3	±3.45	3.0	3.6	0.120
	3-b					41.3			35.0			3.8		0.130
	3-c					44.4			34.3			4.0		0.145
Mix 4	4-a	2037	11.04	22.1	100	33.0	32.9	±1.74	26.7	26.0	±2.09	2.8	2.6	0.138
	4-b					34.3			24.0			2.7		0.116
	4-c					31.5			27.2			2.3		0.089
Mix 5	5-a	2100	10.7	21.45	110	32.7	36.8	±4.17	30.5	29.4	±1.68	3.6	3.4	0.144
	5-b					38.2			27.9			3.6		0.133
	5-c					39.4			29.8			3.1		0.103
Mix 6	6-a	2156	10.4	20.1	115	44.5	44.5	±0.64	33.2	35.0	±1.94	4.1	4.2	0.165
	6-b					44.6			36.0			3.9		0.143
	6-c					44.5			35.9			4.5		0.155
Mix 7	7-a	1814	12.0	24.4	80	26.1	26.1	±0.65	22.8	20.9	±2.07	1.6	1.8	0.057
	7-b					26.2			20.4			2.0		0.066
	7-c					26.0			19.5			1.8		0.060
Mix 8	8-a	1900	11.7	23.8	85	35.0	35.0	±1.03	29.6	27.7	±2.02	2.8	2.6	0.110
	8-b					35.7			27.0			2.6		0.102
	8-c					34.3			26.5			2.5		0.100
Mix 9	9-a	1998	11.2	23.4	90	37.8	37.9	±0.69	30.2	31.6	±1.79	3.1	3.0	0.126
	9-b					37.8			31.6			2.9		0.119
	9-c					38.2			33.1			2.9		0.120

Where, A% = Water absorption ratio, f_{cu} = Compressive strength for cubes, f_c‘ = Compressive strength for cylinders, ν = Shear strength, U_{exp} = Expanded uncertainty, Δ = Maximum slip at shear plane.

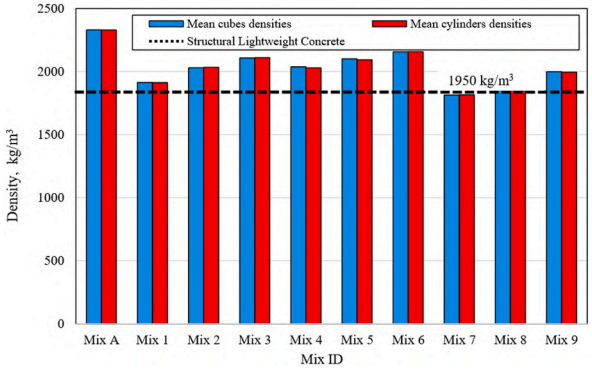


Fig. 10. Density of the studied RPC mixtures at 28 days.

of cement paste was placed on the specimen's surface [56]. The samples were then allowed to air dry for 28 days. After that, the samples were dried for 24 h at 100 °C in an oven, then cooled using a desiccator, and then stored in airtight plastic bags at 25 ± 3 °C and 60 ± 5 % RH in the laboratory until the test is performed. The total measurement time ranged from 15 to 25 s, with the TPS power maintained at 150 mW.

3. Results and discussions

3.1. Workability

The results of the slump test of the RPC mixtures, including superplasticizer, are presented in Table 4. Results showed that the slump value of Mix A (control mixture) was 120 mm, which can be classified as high-workability concrete [57]. For mixtures 1, 2, and 3 at which only sand is replaced by plastic granules, it was noticed that the slump decreased by 25, 20.83, and 8.3 %, respectively, compared to Mix A. Compared to Mix A, for mixtures 4, 5, and 6 at which only gravel is replaced by plastic granules, the slump value decreased by 16.6, 8.3, and 4.16 %, respectively. Finally, for mixtures 7, 8, and 9 at which both sand and gravel are replaced by plastic granules, it was noticed that the slump value decreased by 33.33, 29.16, and 25 %, respectively. All RPC mixtures showed a decreased workability compared to the reference mixture; however, these RPC mixtures still meet the requirements of recommended slump values according to ACI 211.1-91 [57]. Incorporating plastic granules decreases the workability of the new RPC mixtures remarkably, and this reduction rises with the increase in plastic content. This is explained by the fact that plastic has a lower density than natural aggregates, which decreases the mixture's capacity to flow under its own weight [32]. The results obtained are similarly consistent with the findings of Haghighatnejad et al. [58], who reported a decrease in slump value as the PVC aggregate content increased.

3.2. Unit weight

The dry unit weight of the 30 cubes (150 × 150 × 150 mm) and 30 cylinders (150 × 300 mm), three samples per mixture are summarized as shown in Fig. 10, in comparison with the maximum limits of structural light weight concrete [59]. The dry unit weight of the reference mixture was 2330 kg/m^3. For mixtures 1, 2, and 3 at which only sand is replaced by plastic granules, it was noticed that the average density decreased by 17, 13, and 10 %, respectively, compared to Mix A (control mixture). For mixtures 4, 5, and 6 at which only gravel is replaced by plastic granules, the average density decreased by 12.5, 10, and 7.5 %, respectively, compared to Mix A. Eventually, for mixtures 7, 8, and 9 at which both sand and gravel are replaced by plastic granules, the average density decreased by 22, 18.45, and 14 %, respectively, compared to the reference mixture. In general, the results showed that using plastic granules in concrete mixtures decreases its density. This decrease in the density is attributed to the low density of plastic compared to the replaced natural aggregates.

3.3. Porosity and water absorption of RPC mixtures

Open porosity of RPC mixtures is shown in Table 4. According to the results, the reference mixture (Mix A) had an open porosity of 18 %. It was observed that the open porosity increased by 28.3, 25, and 19.4 %, respectively, for mixtures 1, 2, and 3, at which only sand is replaced by plastic granules, in comparison to Mix A. The open porosity increased by 22.7, 19.17, and 11.67 %, respectively, for mixtures 4, 5, and 6 when only gravel was substituted with plastic granules, in comparison to Mix A. Finally, it was observed that the open porosity increased by 35.5, 32.2, and 30 %, respectively, for mixtures 7, 8, and 9, at which plastic granules replace both sand and gravel. The results showed that using plastic granules in RPC mixtures led to lighter and more porous concrete compared to the reference mixture (without plastic granules). This also complies with previous research work [39,60].

The water absorption ratios of RPC mixtures are shown in Table 4. The reference mixture (Mix A) had a water absorption of 8.1 %. For mixtures 1, 2, and 3 at which only sand is replaced by plastic granules, it was noticed that the water absorption increased by 41.9, 35.8, and 33.33 %, respectively, compared to Mix A. Compared to Mix A, for mixtures 4, 5, and 6 at which only gravel is replaced by plastic granules, the water absorption increased by 36.3, 32.1, and 28.4 %, respectively. Finally, for mixtures 7, 8, and 9 at which both sand and gravel are replaced by plastic granules, it was noticed that the water absorption increased by 48.15, 44.4, and 38.27 %, respectively. Generally, it was observed that the water absorption of RPC mixtures increased with the increase in plastic granules,

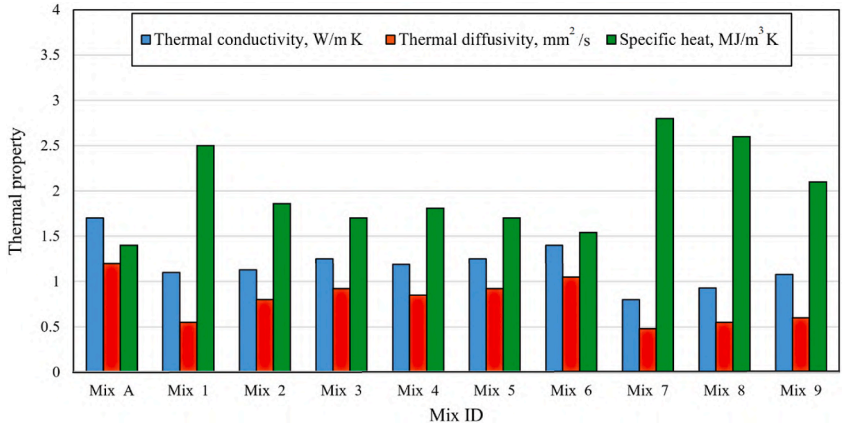


Fig. 11. Thermal properties of the studied RPC mixtures at 28 days.

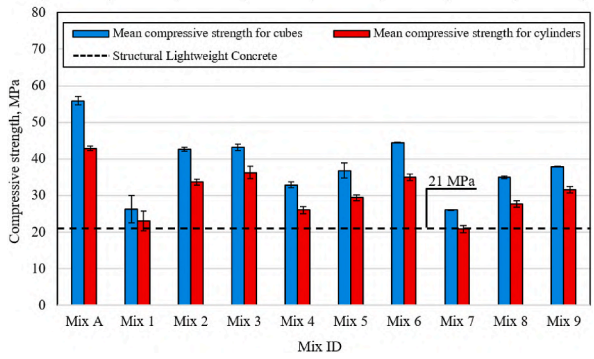


Fig. 12. Compressive strength of the investigated RPC mixtures at 28 days.

which is consistent with the results of previous research [36,60].

3.4. Thermal properties of the RPC mixtures

The thermal properties of 10 RPC (50 × 100 mm) cylinders, one for each mixture, tested regarding the TPS method are presented in Fig. 11. Thermal conductivity, thermal diffusivity, and specific heat of the reference mixture (Mix A) were 1.7 W/ mK, 1.2 m^2/s, and 1.4 MJ/ m^3 K, respectively. Compared to the reference mixture (Mix A), for mixtures 1, 2, and 3, the thermal conductivity decreased by 35.3, 33.5, and 26.4 %, respectively, and the thermal diffusivity declined remarkably by 54.1, 33.3, and 23.3 %, respectively, whereas the specific heat increased by 78.5, 32.8, and 21.4 %, respectively. For mixtures 4, 5, and 6, the thermal conductivity decreased by 30, 26.4, and 17.6 %, respectively; also, the thermal diffusivity declined remarkably by 29.2, 23.3, and 12.5 %, respectively, whereas the specific heat increased by 29.3, 21.4, and 10.0 %, respectively, compared to Mix A. Finally, for mixtures 7, 8, and 9, compared to the reference mixture, the thermal conductivity decreased by 52.9, 45.3, and 36.4 %, respectively, and the thermal diffusivity declined remarkably by 60, 54.2, and 50 %, respectively, whereas the specific heat increased by 100, 85.7, and 50 %, respectively. Generally, the results showed that the thermal conductivity and thermal diffusivity are directly proportional to density; however, the specific heat is inversely proportional to density. Compared to conventional concrete. The decrease in thermal conductivity and thermal diffusivity improves thermal isolation, which leads to cooling/heating energy conservation for buildings. The enhanced thermal characteristics may be due to the low density of the RPC, which affects the thermal properties; in addition, it is attributed to the low thermal conductivity of the plastic if compared with natural aggregates.

3.5. Mechanical properties of the RPC mixtures

Table 4 shows the average test results of compressive strength, shear strength, and the maximum slip at the shear plane of the various RPC mixtures. The results of each part are explained separately in the following section. Also, Table 4 shows the expanded uncertainty pertaining to the compression tests of cubes and cylinders.

3.5.1. Compressive strength

Fig. 12 presents the effect of incorporating plastic granules in the compressive strength of cubes of RPC mixtures. The cubic compressive strength of the reference mixture was 55.9 MPa. For mixtures 1, 2, and 3, compared to Mix A (reference mixture), the

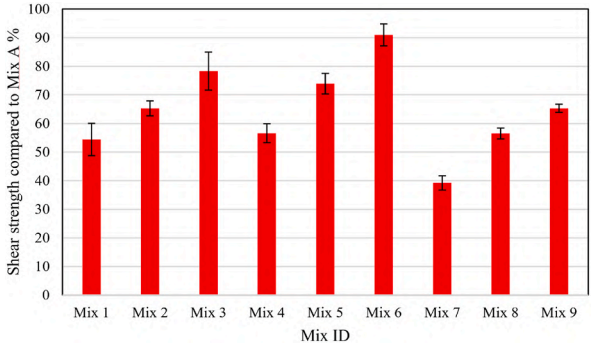


Fig. 13. Shear strength of the RPC mixtures compared to the reference mixture.

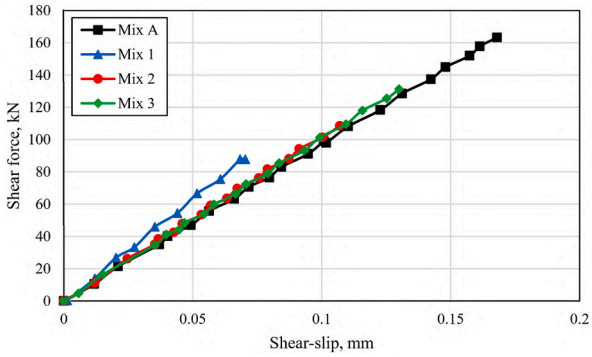


Fig. 14. Load versus shear-slip of the RPC mixtures, Control mixture and Group (1).

cubic compressive strength decreased by an average of 52.9, 23.8, and 22.7 %, respectively. For mixtures 4, 5, and 6, compared to the reference mixture, the compressive strength dropped by an average of 41.1, 34.1, and 20.3 %, respectively. Eventually, for mixtures 7, 8, and 9, compared to Mix A, the compressive strength dropped by an average of 53.3, 37.3, and 32.2 %, respectively. Fig. 12 shows the compressive strength of cylinders of RPC mixtures in comparison with the minimum strength of structural lightweight concrete determined by ACI 213R-14 [59]. The compressive strength of the reference mixture was 42.9 MPa. For mixtures 1, 2, and 3, compared to the reference mixture (Mix A), the cylinder compressive strength decreased by an average of 46.3, 21.4, and 15.3 %, respectively. Compared to Mix A, for mixtures 4, 5, and 6, the cylinder compressive strength dropped by an average of 39.4, 31.4, and 18.4 %, respectively. Finally, for mixtures 7, 8, and 9, compared to the reference mixture, the cylinder compressive strength decreased by an average of 51.3, 35.4, and 26.3 %, respectively. It was noted that, due to the light weight of the plastic compared to natural aggregates. There was a noticeable decrease in the density of some mixtures (Mix 1, and 8) so that they could apply the requirements of structural light weight concrete; dry density equals (1350–1950 kg/m^3) and cylinder compressive strength equals (21–35 MPa) according to ACI 213R-14 [59]. Based on the visual inspection during mixing of Mix 1, granular separation was observed. This was induced by the low weight of plastic granules, which led to bounce these particles away and made the mixture inhomogeneous, which led to an obvious variation in the compressive strengths of the tested samples. All previous studies [27–35] confirmed that using plastic granules as a partial replacement of natural aggregate with high percentages decreases the compressive strength of the RPC mixtures. The strength reduction regarding the use of plastic granules in the RPC may be due to the low stiffness of plastic granules compared to the natural aggregates' stiffness and the weak interfacial transition zone caused by the weak bond between the plastic granules and matrix.

3.5.2. Shear friction strength

Since the natural aggregates play an important role in shear strength [61], therefore the replacement of the natural aggregates by plastic granules showed a significant impact. Fig. 13 shows the effect of incorporating plastic granules in the shear strength of RPC mixtures. The shear friction strength of the reference mixture (Mix A) was 4.6 MPa. For mixtures 1, 2, and 3, compared to the benchmark mixture, the average shear strength decreased by 45.6, 34.7, and 21.7 %, respectively. For mixtures 4, 5, and 6, compared to Mix A, the shear strength dropped by an average of 43.4, 26.1, and 9 %, respectively. Compared to the reference mixture, mixtures 7, 8, and 9, the average shear strength decreased by 60.8, 43.5, and 34.7 %, respectively. It was noticed that increasing the replacement ratio led to a decrease in shear strength for all tasted samples. This reduction in shear strength is caused by the lack of natural aggregate, which results in a lack of aggregate interlock. Figs. 14–16 show load vs. shear-slip curves for all tested S-shape specimens. In general, the shear-slip was linearly proportional to the shear load, as shown in the load shear-slip curves. After the initiation of the first crack, the crack propagated instantly, then a sudden collapse of the sample took place; this is due to the absence of transverse

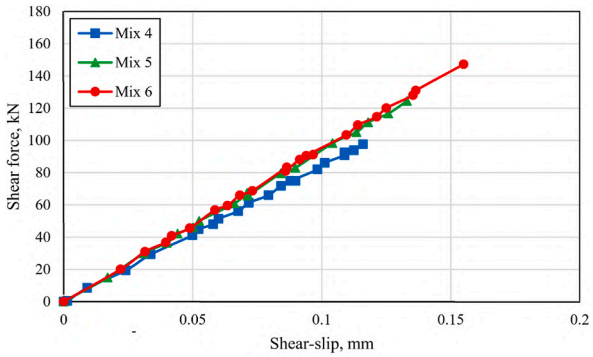


Fig. 15. Load versus shear-slip of the RPC mixtures, Group (2).

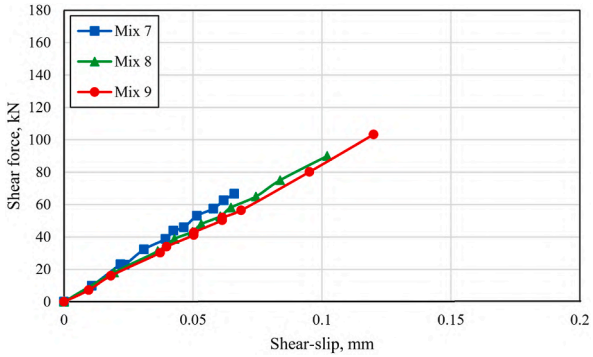


Fig. 16. Load versus shear-slip of the RPC mixtures, Group (3).



Fig. 17. S-shape specimen at failure.

reinforcement across the shear plane. Fig. 17 presents the cracking pattern at failure of a tested sample.

3.6. Statistical analysis

A statistical analysis was carried out considering compression and shear strengths, the amount of consumed plastic, density, and thermal conductivity to determine the optimum design of the studied mixtures. Regarding previous research works [56,62], commercial software **(Minitab18)** was used to improve the experimental design plan by the Taguchi method [63]. Previous research works [64–66] used the Taguchi method (single-response optimization) as a reliable procedure to determine the optimal manufacturing parameters to improve product properties. The commonly known features of Minitab18 are called ‘‘larger-is-better’’ in which the superiority of compression and shear strengths and the consumed amount of plastic are chosen, while ‘‘The-smaller-the-better’’ feature is activated for density and thermal conductivity. The program features are based on logarithmic functions and can be addressed as follows: Eqs. (1) and (2) [63]:

Table 5
Input data of Minitab18 software.

Mix ID	Input regarding to parameters		Input regarding to the test outputs				
	Sand Replacement ratio%	Gravel Replacement ratio%	Compressive Strength (MPa)	Shear strength (MPa)	Plastic amount (kg/m^3)	Density (kg/m^3)	Thermal conductivity (W/ mK)
Mix A	0 %	0 %	55.9	4.6	0	2330	1.70
Mix 1	100 %	0 %	26.3	2.5	265	1913	1.10
Mix 2	80 %	0 %	42.6	3.0	212	2030	1.13
Mix 3	60 %	0 %	26.3	3.6	159	2107	1.25
Mix 4	0 %	50 %	32.9	2.6	199	2037	1.19
Mix 5	0 %	40 %	36.7	3.4	159	2100	1.25
Mix 6	0 %	30 %	42.6	4.2	120	2156	1.40
Mix 7	100 %	30 %	26.1	1.8	385	1814	0.80
Mix 8	80 %	30 %	35.0	2.6	331	1900	0.93
Mix 9	60 %	30 %	37.9	3.0	278	1998	1.08

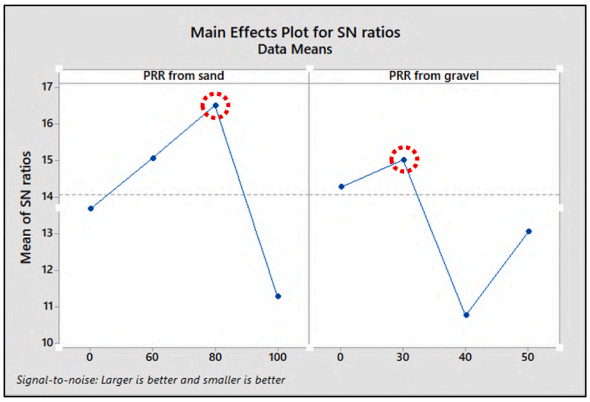


Fig. 18. Analysis results of Minitab18 software.

$$\text{“The}-\text{larger}-\text{the}-\text{better''}\ S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{1}$$

$$\text{“The}-\text{smaller}-\text{the}-\text{better''}\ S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{2}$$

Where: y denotes the measured experimental value of the experiments, and n denotes the number of times each experiment is duplicated.

Table 5 determines the input data regarding parameters and the test outputs. In this analysis, the main goal is to determine the optimum replacement ratios to maximize the required strengths (compressive and shear strengths) and the consumed plastic amount and to minimize the required density and thermal conductivity. To evaluate the impact of each individual parameter and its contribution, the response table (Taguchi analysis) was supplied with the experimental outputs at each parameter level. The analysis of Minitab18 is shown in Fig. 18. The analysis outputs show that the best combination from sand/gravel replacement ratios is 30 % replacement of sand simultaneous with 80 % replacement of gravel. This result indicates that the optimum replacement proportions mixture based on the experimental outputs can be obtained via the replacement ratios used in Mix 8.

4. Conclusion

In this study, the influence of using plastic granules as a partial replacement of natural aggregates by volume has been studied. The physical and mechanical properties of the newly developed RPC mixtures have been studied by carrying out an experimental program in which one reference mixture and nine RPC mixtures were involved. Also, statistical analysis was performed to determine the optimum plastic replacement ratio. Based on the results of this study, the main conclusions can be summarized as follows.

1. Incorporating plastic granules in RPC mixtures decreases both the compressive and shear strengths. When replacing sand only with plastic, compared to the reference mixture, there was a decrease in compressive strength up to 52.9 % and a decrease in shear strength up to 45.6 %. By comparing to the control mixture, replacing gravel only led to a decrease in compressive and shear strengths up to 41.1 % and 43.4 %, respectively. This reduction is owing to the lack of aggregate interlock for plastic granules compared to natural aggregates.
2. Using plastic granules has a significant effect on the thermal properties of RPC mixtures; as the plastic content increases, the thermal properties show more enhancement. The enhanced thermal properties may be due to the low thermal conductivity of plastic compared to natural aggregates.
3. The natural aggregate replacement by plastic granules in RPC mixtures resulted in lighter concrete compared to the conventional one, as the density decreased by a ratio ranging between 7.5 and 22 % compared to the reference mixture.
4. The Taguchi analysis (single-response optimization) carried out by Minitab18 showed that the best sand/gravel replacement ratios is 30 % replacement of sand simultaneous with 80 % replacement of gravel. This result indicates that the optimum mixture based on the experimental outputs can be obtained via the replacement ratios used in Mix 8.
5. The best mixture based on the statistical analysis (Mix 8) has a dry density of 1900 kg/m^3 and compressive strength of 27.7 MPa can be classified as a structural light weight concrete, as it meets the requirements of structural lightweight concrete: dry density (1350–1950 kg/m^3) and compressive strength (21–35 MPa) as per ACI 213R-14. This structurally lightweight RPC contributes to reducing the cost of reinforcement; therefore, it is not only beneficial for structural purposes but also supports the environment.

CRediT authorship contribution statement

Karem E. El-Aidy: Writing – review & editing, Supervision, Project administration, Methodology, Data curation. **Mohamed**

Ellithy: Writing – review & editing, Validation, Supervision, Project administration, Methodology. **Mohamed H. Mahmoud:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation. **Tarek F. El-Shafiey:** Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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