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Properties of Cement Mortar Containing Recycled High-Density Polyethylene (HDPE)

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Abstract Millions of tons of plastic waste are generated globally, and only about 10 percent of it is recycled. It is crucial to segregate and circulate plastic waste and repurpose it for countless other uses. There are many ways to repurpose and reuse these discarded plastics. One use that can be examined is the use of plastic as a partial sand replacement in cement mortar. To contribute to this important and valid discourse, this research studies the mechanical and thermal properties of cement mortar that incorporates recycled high-density polyethylene (HDPE) particles. Different percentages (0%, 4%, 6%, and 10%) of sand replacement by volume with recycled HDPE particles are tested. Two different cement-sand ratios are investigated: 1:3 and 1:6. The experiments include compressive and indirect tensile strengths, unit weight, and thermal conductivity. Experimental results show that the increase in plastic content in mortar mixtures results in a decrease in the compressive and tensile strengths as found in the literature. On the other hand, a decrease in the thermal conductivity of the cement mortar that incorporates HDPE particles is also observed. For HDPE/sand replacement of 10% and cement to sand at a ratio of 1:3, the reduction in the thermal conductivity coefficient k is 50%. For HDPE/sand replacement of 10% and cement to sand at a ratio of 1:6, the reduction is 32%. This reduction is of significance as the cement mortar is usually used for stucco. When used for southern façades in arid climate countries like Egypt, producing stucco with such low thermal conductivity will result in a reduction in energy consumption for the AC. Moreover, the aesthetic value of the colored stucco may lead to the elimination of the painting process, not to mention the positive impact on the environment.

Keywords Plastic Waste, Recycling, HDPE Mortar, Plastering

1. Introduction

The recycling of plastic wastes is an imperative need nowadays. Previous research done on the inclusion of plastic aggregate into concrete or mortar mixtures has shown some advantages as well as disadvantages. However, the use of High-Density Polyethylene (HDPE) which is a type of polymer, has not been fully assessed in terms of its use as a non-traditional coarse or fine aggregate replacement. HDPE has many advantages when compared to traditional materials. These advantages include lighter weight because of lower density, lower tensile modulus, lower cost, easier manufacturing, and better biocompatibility [1]. One way to cater to the high demand for aggregates is by finding a replacement of natural, traditional aggregates, either fully or partially. One of the abundant materials to be used instead of regular aggregates is recycled plastic, which consequently can reduce the negative impacts of the utilization of natural aggregates, but also helps in solving the major issue of plastic waste [2]. Previous studies, as will be discussed below, have investigated the use of recycled plastics in concrete and mortar mixtures using different percentages as full or partial replacement of sand by recycled plastic. These mixtures have been tested with varying conditions such as water/cement ratios, sand type, cement type, plastic-type, processing of the collected plastic, either using cutting or melting methods, and whether any admixtures were added.

2. Recycled Plastic Use in Concrete and Mortar

One way to cater to the high demand of aggregates is by finding a replacement of natural, traditional aggregates, either fully or partially. One of the abundant materials to be used instead of regular aggregates is recycled plastic, which consequently can reduce the negative impacts of the utilization of natural aggregates, but also helps in solving the major issue of plastic waste [2]. The utilization of plastic waste in the construction industry has gained recognition as this movement can extraordinarily counteract plastic pollution issues. Furthermore, plastic waste replaces regular aggregate in the production of construction materials. Using this method, plastic waste is not involved in any rigorous recycling treatment, and it could be directly used as a replacement for conventional aggregate [3].

Previous studies were conducted on both concrete and mortar mixtures containing recycled plastic of various types such as polycarbonate (PC) [4], polyethylene terephthalate (PET) [4,5,6,7] and high-density polyethylene (HDPE) [8,9,10]. Some plastics were lightly washed and grounded using a blade mill [5,6,7,10] and others were melted at high temperatures, extruded, and cut to the desired size [5,9,11]. Furthermore, the replacement of the sand was volume-based replacement [4,5,9,10] or weight-based replacement [6,7]. The replacement varied from 0% to 100% and the size of the plastic used in the mixtures ranged from 0.075 to 5 mm. The mechanical properties tested in the majority of the previous studies proved that the compressive strength in concrete decreases as the sand/plastic replacement increases. For example, in the work done by Almesha et al., [7] the PET replaced sand in concrete mixes by 10%, 20%, 30%, 40%, and 50% results in reduction in compressive strength by 1.2%, 4.2%, 31%, 60%, and 90.6% respectively [7]. On the other hand, one research suggested an increase in the compressive strength when using virgin HDPE granules with a maximum sand substitution as low as 3% [8]. The same trend was also observed in mortar mixtures with PET/aggregate replacement by 3%, 10%, 20% and 50% resulting in reduction in compressive strength by 9.8%, 30.5%, 47.1% and 69%. For PC/aggregate replacement for concrete mixtures by 3%, 10%, 20% and 50% led to reduction in compressive strength by 6.8%, 27.2%, 46.1% and 63.9% respectively [4]. Another study conducted by Aocharoen and Chotickai [9], were they used a PC/aggregate replacement by 15% resulted in reduction in compressive strength by 16.24% and 14.87% for ages 7 and 28 days respectively. Furthermore, according to Da Silva et al., [5], a higher reduction in compressive strength when using PET plastic flakes was reported compared to plastic pellets for 10% sand substitution. This can be attributed to plastic flakes being more irregular and thinner and so more deformable.

Similar trends were also reported in tensile strength with increase in plastic content in concrete by 10.6%, 35.4%, and 85.5% for the 10%, 30%, and 50% PET concrete mixes [7]. However, one research suggested an increase in tensile strength with the use of virgin HDPE granules [8]. Furthermore, according to Frigione [6], tensile strength also slightly decreased in the same manner as the compressive strength. Moreover, it was found that higher values of water/cement ratios contribute to lower tensile and compressive strengths. The factors accountable for the reduction in compressive strength and tensile strength of concrete and mortar with plastic aggregate are due to; the low bond strength between the plastic aggregates and cement paste, the difference in the particle size distribution of plastic aggregates and natural sand, hydrophobic nature of plastic aggregates, and porosity induced by inappropriately graded plastic aggregates

Lastly, thermal conductivity was seen to decrease therefore suggesting better insulation according to Boucedra et al., [11]. There was an overall enhancement in the thermal conductivity of the tested concretes when the plastic content increased. The thermal conductivity of river sand concrete was higher than that of dune sand concrete. Another study by Badache et al., [10] suggested that after 1 year, the replacement of 15%, 30%, 45%, and 60% of natural sand by HDPE reduced the thermal conductivity by 10%, 20%, 31%, and 41%, respectively, compared to the traditional mortar.

All the previous research in the literature has confirmed some properties that are relevant to the current study and an optimum mixture of mortar components was extrapolated. Concrete and mortar mixtures containing waste plastics showed decreased thermal conductivity which is beneficial for countries with arid environments. Moreover, improved acoustics as plastic percentage increases in the waste plastic concrete mixture was reported.

Another factor that was enhanced in waste plastic mixtures compared to conventional concrete and mortar mixtures was the lower density which is expected since plastics have lower density compared to natural aggregates. There is a common trend of decreased compressive strengths as the quantity of plastic increases in the concrete and mortar mixtures, but the decrease in most mixtures having plastic percentage less than 15% is similar to conventional mixtures. However, there was an increase in compressive strength in one concrete mixture containing 3% HDPE granules. Moreover, the same trends observed in compressive strength are recurring in tensile strength.

To conclude, since there is a manageable decrease in compressive and tensile strengths, plastic waste concrete can be used in non-structural elements or lightweight structural elements and mortars can be used as lightweight, thermo-acoustic plastering. Furthermore, HDPE in mortar mixtures has not been tested extensively and according to the minimal research done, HDPE might be a better alternative when used as an aggregate compared to other plastics such as PET or PVC.

3. Research Methodology

The research aims to investigate the mechanical and thermal properties of the cement mortar that incorporates HDPE particles. Scrap HDPE bottles are collected. The HDPE plastics are usually used for detergent, shampoo and cleaning supply bottles. The bottles are cleaned using tap water before they are cut to more manageable pieces. The shredding starts by cutting the large bottles into manageable pieces. The large pieces are then shredded into smaller pieces. These pieces are fed into a knife mill that cuts the plastic into the desired sizes which are closer to the sand particles size. The machines used for the three stages cutting process are shown in Fig.1. The last two stages for shredding the HDPE bottles are shown in Fig. 2. The particle size distribution curve of the shredded HDPE is given in Fig. 3. The sand: cement proportions for cement mortar according to ASTM C1329-05 [12] and ES 2421-7 / 2020 [13] is 3:1 and water/cement ratio (W/C) is 0.4. The cement used is CEM I 42.5 and sand is desert sand with specific gravity (SG) of 2.5. The HDPE density is 0.95 gm/cm^3. Another mix proportion is tested based on the local practice of walls plastering in the construction industry in Egypt. Usually, the stucco mix proportion cement: sand equals 1:6 and water/cement ratio is 0.5. For this mix trail, 10% HDPE sand replacement is chosen to be applied. This mix is tested mainly for thermal conductivity.

Figure 1. HDPE shredding: (top) knife mill; (middle) pieces cut using the saw;(bottom) saw machine

Figure 2. HDPE shredding: (top) Small sized plastic pieces; (bottom) Sand like plastic grains

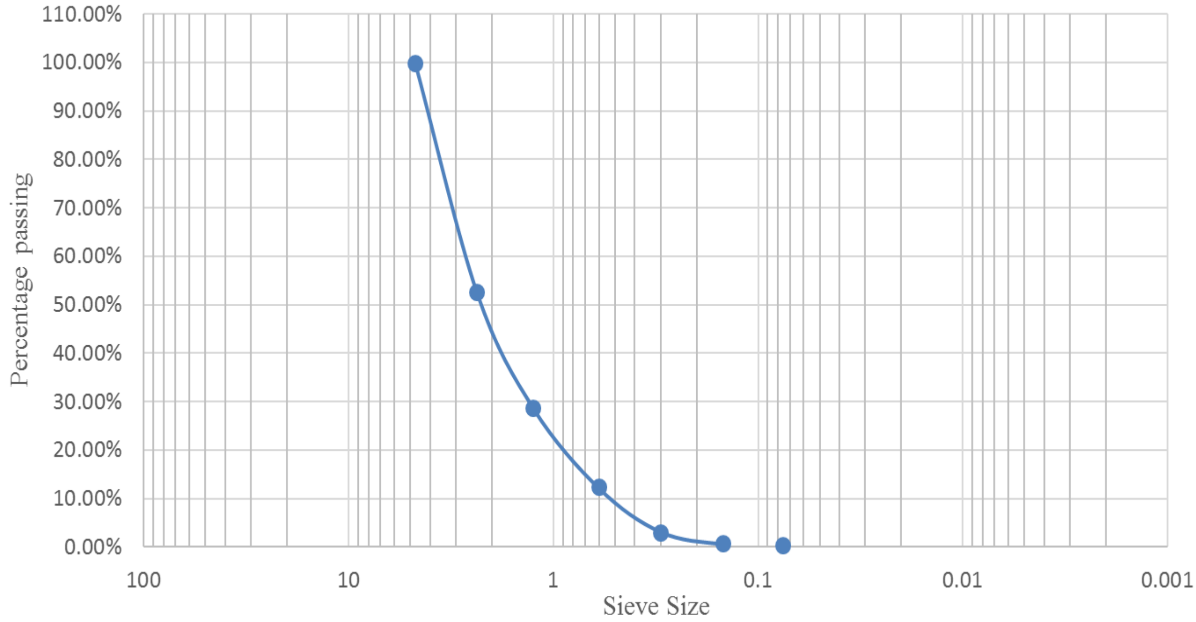

Figure 3. Particle size distribution of HDPE

The HDPE particles are meant to replace sand by 4%, 6%, 10% by volume. A 0% replacement mix represents the control specimen. The tested mechanical properties include compressive and tensile strengths, and for the physical properties the thermal conductivity is tested. All the tests and readings are conducted at age of 7 days.

Table 1. Standard cement mortar mix proportions

Ratio	Cement (g)	Water (g)	Sand (g)	HDPE (g)
	1	0.4	3	
Compressive strength specimen mix proportions for cement: sand = 1:3				
0%	185	74	555	0
4%	185	74	546.1	8.9
6%	185	74	542.3	12.7
10%	185	74	533.9	21.1
Thermal Conductivity specimen mix proportions for cement: sand = 1:3				
0%	242.7	97.08	728.1	0
4%	242.7	97.08	717	11.1
6%	242.7	97.08	711.5	16.6
10%	242.7	97.08	700.4	27.7
Tensile Strength specimen mix proportions for cement: sand = 1:3				
0%	847.2	338.9	2541.7	0
4%	847.2	338.9	2503.1	38.6
6%	847.2	338.9	2483.7	58
10%	847.2	338.9	2445.1	96.6
Thermal Conductivity specimen mix proportions for cement: sand = 1:6 (stucco mix proportions)				
10%	138	55.3	799.4	31.6

For compressive strength, the specimens are (7x7x7) cm cubes according to ES 2421-7 / 2020 [13]. The indirect tensile strength test is performed on a 5cm diameter cylindrical specimen with height 20 cm. Three specimens for every percentage are tested and the average is calculated.

The thermal conductivity test is conducted on a 15x15x2 cm tile using a Heat Flow Meter instrument at The Housing and Building National Research Center (HBRC). The Thermal conductivity is defined as the ability of a certain material to conduct heat. It is measured using either a steady state method or non-steady state method. In the steady state method, which is adopted in this research, the sample is placed between two plates; one plate is heated and the other is cooled. Upon reaching constant values of temperature of both plates, the steady state temperature, the thickness of the sample and the heat input to the hot plate are used to evaluate the thermal conductivity of the sample. Figure 4 shows a schematic of the procedure. The equation to calculate the thermal conductivity is as follows:

$$k=QL/A\Delta T \quad (1)$$

where,
k = Thermal conductivity in W/mK.
Q= heat transfer rate in Watt.
L= thickness of specimen in meter.
ΔT= temperature difference in Kelvin.
A = cross sectional area of specimen in m^2

In this research, the thermal conductivity test is conducted on a Laser Comp Heat Flow Meter (LCHFM). The LCHFM utilizes a steady state technique for the determination of thermal conductivity. The Heat Flow meter method, designed specifically for insulating materials, is defined by ASTM C518-17 [14], ISO 8301:1991 [15], and DIN EN 12667 (2001) [16]. This cost-effective and practical method is widely recognized and preferred by industry professionals throughout the world for its speed, simplicity, and accuracy.

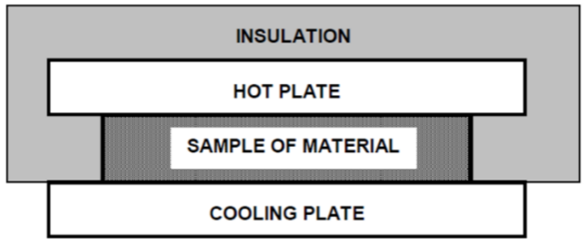

Figure 4. Scheme of set up to determine the thermal conductivity for steady state case

4. Results

The dry density of the samples is determined, and the results show reduction ranging from 4% to 8% according to the HDPE sand replacement percentage.

Figure 5 presents the compressive strength for the three different HDPE/sand replacement percentages compared to the control specimen with no HDPE. It can be concluded that the sand replacement with HDPE decreases the cement mortar strength by 64% and as the percentage increase the degradation of the mortar strength increased. The reduction reaches 75% for samples with 10% HDPE sand replacement. These results comply with the literature.

The same comment can be said for the indirect tensile strength with 70% reduction for 4% replacement, 66% for the 6% and 64% for the 10% HDPE content. Figure 6 shows the indirect tensile strength for the four mixes.

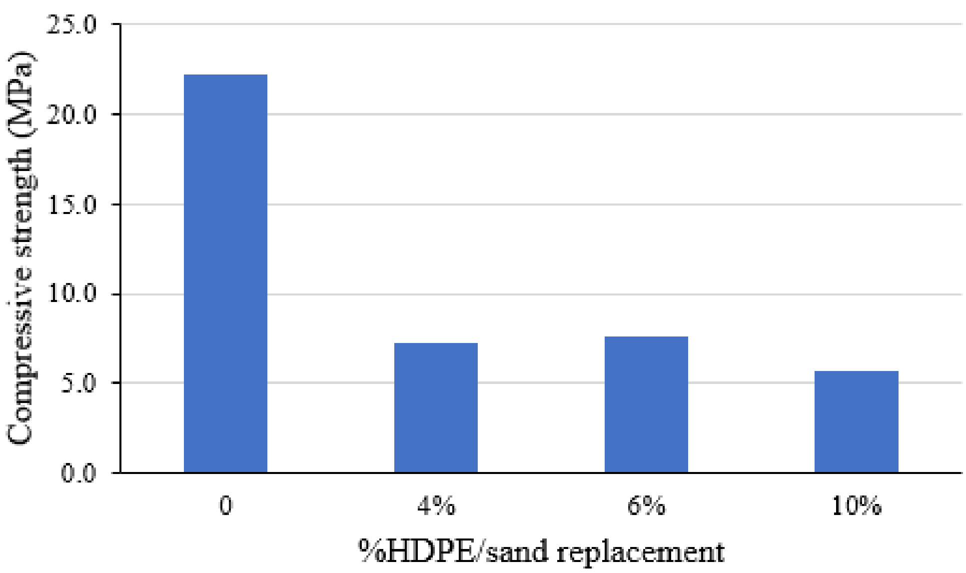

Figure 5. The compressive strength for the three percentage of HDPE/sand replacement

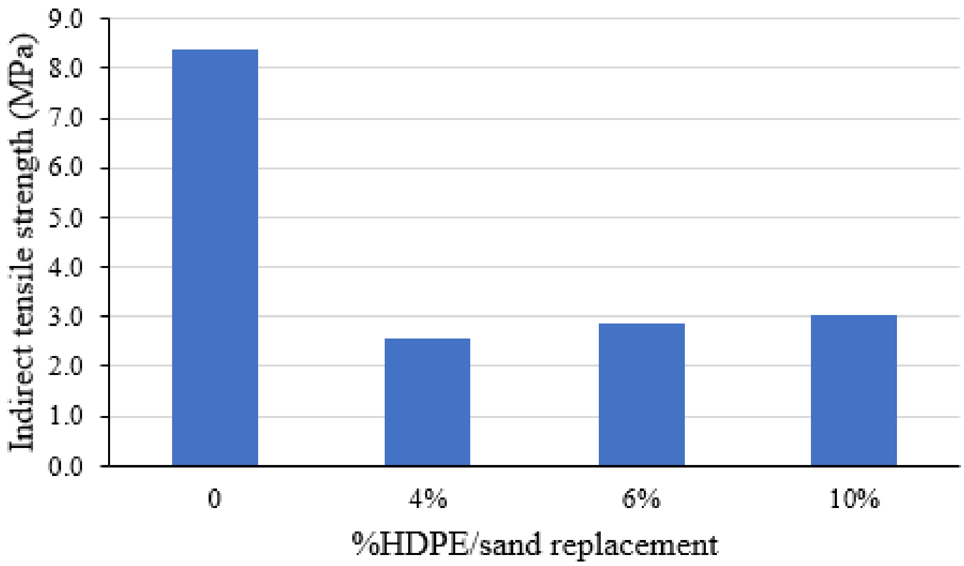

Figure 6. The indirect tensile strength for the three percentage of HDPE/sand replacement.

As the application of cement mortar in construction industry mainly is in the walls stucco or walls construction, the strength requirement is not of a primary interest. The main target is to produce a finishing material with lower thermal conductivity and aesthetically pleasing to eliminate the need of painting specially in the facades that are subjected to sun rays for long hours particularly in arid climates.

This target is achieved in the innovative material developed in this research. The results for the thermal conductivity test are presented in Table 2 for the control specimen and the 10% sand replacement specimen. The thermal conductivity for the control specimen with ingredients conformable with the specification is in good agreement with the value found in the work of Xu & Chung [17]. The reduction in the thermal conductivity is 50% for the mixture with cement to sand ratio of 1:3 and 10% HDPE / sand replacement. For the stucco proportion of cement to sand 1:6, the reduction in the thermal conductivity is 32%. To investigate the reason behind that the reduction in the thermal conductivity is not enhanced for the cement to sand ratio of 1:6 mix, the weights given in Table 1 are transformed to volume ratios using the specific gravity of each component in the mix. The weighted volumes of the mix ingredients are given in Table 3. From Table 3 it can be concluded that the stucco mix (cement: sand 1:6) is the mix with the highest volume fraction of sand. Per Table 3, sand has the highest thermal conductivity among the mix ingredients. This is reflected in the value of the thermal conductivity of the stucco mix. However, the implementation of the HDPE in the 1:6 mix mitigates the situation and reduces the thermal conductivity coefficient with 32% compared with the control mix. This will certainly have an impact on the thermal comfort inside the buildings and will significantly reduce the electricity consumption for AC systems. Figure 7 shows the tile used for the thermal conductivity determination.

Table 2. Thermal conductivity test results.

Specimen	Thermal conductivity (W/mK)
0% HDPE (control specimen)	0.5
10% HDPE for cement: sand 1: 3	0.25
10% HDPE for cement: sand 1: 6	0.34

Table 3. Weighted volumes of mix ingredients

Criteria	Ingredient			
	cement	Water	sand	HDPE
Specific gravity	3.15	1	2.5	0.955
Thermal conductivity (W/mK)	0.53 [17]		1.4 [18]	0.5
cement: sand = 1:3 mix with 0% HDPE				
Weight of ingredients (gm)	242.7	97.08	728.1	----
Volume of ingredients (cm^3)	77.05	97.08	291.24	-----
Weighted volume	0.166	0.209	0.625	-----
cement: sand = 1:3 mix with 10% HDPE				
Weight of ingredients (gm)	242.7	97.08	700.4	27.7
Volume of ingredients (cm^3)	77.05	97.08	280.16	29.47
Weighted volume	0.16	0.2	0.579	0.061
cement: sand = 1:6 mix with 10% HDPE				
Weight of ingredients (gm)	138	55.3	799.4	31.6
Volume of ingredients (cm^3)	43.8	55.3	319.76	33.61
Weighted volume	0.1	0.122	0.707	0.0743

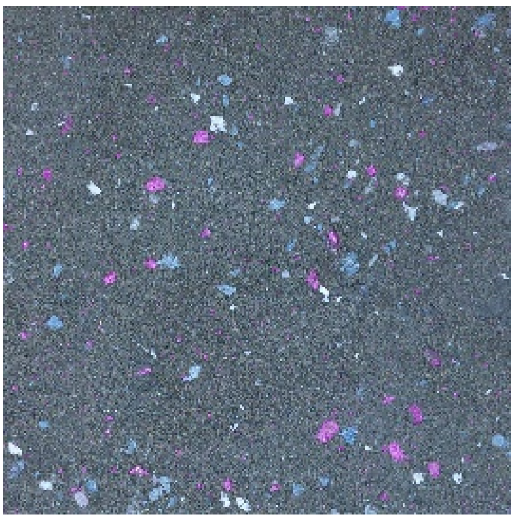

Figure 7. Thermal conductivity determination tile.

A questionnaire is prepared for architects to investigate the potential of using the cement mortar incorporating HDPE particles for façade finishing. The responses reveal that the aesthetic aspect in the developed materials is of acceptance considering its low thermal conductivity specially for the facades that is more prone to sun heat.

5. Conclusions

The scrap HDPE is exploited to produce cement mortar with lower thermal conductivity. The research replaced sand with recycled shredded and minced high density polyethylene bottles with almost no further treatment. The replacement percentages are 4%, 6%, and 10%. The experimental results show reduction in the compressive and indirect tensile strength with about 60-70%. However, strength is not a crucial property for plastering material. Meanwhile, the thermal conductivity is reduced with about 50% for cement to sand mix of 1:3 and 10% HDPE - Sand replacement. And for cement to sand mix 1:6 and 10% HDPE - Sand replacement, which is the common stucco mix in Egypt, the thermal conductivity reduction is 32%. This certainly will have an impact on the AC requirements especially for an arid climate like Egypt in addition to the environmental effect by recycling a non-degradable material link HDPE. The aesthetically pleasing looking of stucco with HDPE colored particles may lead to exclusion of paintings of facades which reduces the construction time and cost.

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