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Strength prediction model for cement mortar made with waste LDPE plastic as fine aggregate

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ABSTRACT

Non-biodegradable aggregate prepared from low density polyethylene (LDPE) plastic was used as partial replacement for sand in cement mortar. Various volumetric fractions of 0, 5, 10, 20, 30, 40, 50, and 60% sand were replaced using ground LDPE waste plastic. Mortar mixtures of 1 : 3 cement to fine aggregate were prepared at various water /cement ratios of 0.45, 0.50, 0.55 and 0.60, then used to cast 50 mm cubes and 40 × 40 × 160 mm prisms. It was found that strength reduces significantly as the proportion of LDPE in mortar increases, however, mixtures containing 50 to 60% LDPE satisfy the strength criteria for masonry mortars. Based on experimental data, a model was proposed for predicting the compressive strength of mortars containing waste plastics. The model's validation gave generally accurate predictions for the strengths of mortars made using different types of plastics.

Keywords: LDPE mortar, plastics as aggregates, compressive strength, prediction model

1. Introduction

Disposal of waste plastics (WP) has become an important issue globally due to unabated growth in the use of plastics and their non - biodegradable nature. Annual consumption of plastics in Western Europe is about 60 million tons, which results in about 23 million tons of waste plastics (Iucolano et al., 2013). In Korea alone, 2.2 billion polyethylene terephthalate (PET) bottles are produced annually, representing about 87000 tons of PET waste (Choi et al., 2009). South Africa's annual consumption of plastics amounts to 1.6 million tonnes, out of which only about 20% is recycled (DTI, 2015). India reportedly produces over 25,000 tonnes of waste plastic a day (IEM, 2017). Utilizing WP in the production of cementitious materials would contribute towards mitigation of the adverse effects of plastics on the environment. Some limited researches on application of WP as aggregates in concrete have recently been reported in the literatures (Batayneh et al., 2007; Marzouk et al., 2007; Suganthy et al., 2013; Ohemeng et al., 2014; Ohemeng et al., 2015). Generally, research on WP is part of the general theme on re-use and recycling of wastes in search for more sustainable alternatives needed to mitigate observed adverse impacts of industrialization associated with environmental pollution, high CO_2 emissions and climate change.

In an investigation by Guendouz et al. (2016), low density polyethylene (LDPE) plastic was incorporated as partial replacement of fine aggregates in concrete. It was reported that the bulk density of concrete decreased from 2090 kg/m^3 for the control to 1900 kg/m^3 for the mixture containing 40% LDPE by volume, representing a reduction of 9.1%. Interestingly, they reported a 30% increase in compressive strength upon incorporation of 20% LDPE as fine aggregate, while the flexural strength correspondingly increased from 3.5 MPa for the control to 5.0 MPa for the LDPE concrete. However, various other researches (Sule et al., 2017; Flomo, 2013; Sojobi and Owamah, 2014) show that both density and strength decrease with incorporation of LDPE in mortar or concrete, regardless of the LDPE proportion.

A study by Sule et al. (2017) showed a 9% reduction in density of concrete owing to incorporation of 20% LDPE as fine aggregate in the mixture. The 28-day compressive strength of the concrete also decreased by 53.3% from 20.6 MPa for the control to 9.6 MPa for the mixture containing 30% LDPE plastic. Flomo (2013) similarly reported a reduction of 29% in density and of 48% in compressive strength of mortars upon incorporation of 40% LDPE as fine aggregate. In a study done by Sojobi and Owamah (2014), a concrete mixture comprising 1 : 1 : 2 cement to sand to coarse aggregate, showed a reduction in density from 2620 kg/m^3 for the control to 2415 kg/m^3 for the 15% LDPE mixture, while its 28-day compressive strength decreased from 47 MPa to 27 MPa respectively. An investigation conducted by Rumšys et al. (2017) on lightweight concrete made using recycled PET and using expanded clay aggregates, reported a low density of 2044 kg/m^3 for the former and a higher density of 2932 kg/m^3 for the latter.

As seen in the foregoing, various physical properties of mortar and concrete are affected when fine aggregates are partially or fully replaced with WP. The observed reduction in density as reported in the various literatures, can be attributed to the low specific gravity of plastic, being much less than that of natural sand (Section 2.1, Table 2).

Ghernouti and Rabehi (2012) investigated the strength of mortars containing waste plastic bags (WPB). It was reported that the 28-day compressive strength of mortar decreased from 45 MPa for the control to 25 MPa for the 40% WPB mortar. For the same mixture, flexural strength decreased from 8.1 MPa for the control to 4.3 MPa for the WPB mortar, a decrease of 47%. Similarly, Wang and Meyer (2012) reported that replacement of sand with high impact polystyrene (HIPS) in mortar, reduced its mechanical properties. When 10, 20, and 50% of sand volume was substituted with HIPS, there were compressive strength reductions of 12, 22, and 49%, respectively. Also, Choi et al. (2009) reported that the 28-day compressive strength of mortar reduced from 45 MPa for the control mixture to 40 MPa and 34 MPa for mixtures containing 25% and 50% PET as fine aggregate, respectively.

A study by Hannawi et al. (2010) reported a reduction in fresh and dry density of mortar with increase in the content of WP incorporated as fine aggregate. The values of dry density decreased from 2173 kg/m^3 for control mixture to 1755 kg/m^3 and 1643 kg/m^3 for mixtures containing 50% PET and 50% polycarbonate plastic (PLC) as fine aggregates, respectively. They also reported a decrease in compressive strength, flexural strength and elastic modulus, when the content of WP fine aggregates in the mortar mixtures increased. Compressive strength reductions of 9.8, 30.5, 47.1, and 69.0% were reported for mixtures containing 3, 10, 20, and 50% PET aggregates, respectively.

From the literature discussed in the foregoing, it is evident that waste utilization of LDPE or WP generally in concrete, is currently a subject of major research interest. As a scientific contribution to the subject, the present study was conducted to investigate the potential use of waste LDPE plastic as a substitute for sand in cement mortars. Various physical and mechanical properties of LDPE mortar were measured including density, compressive strength, flexural strength and water absorption. The data generated from the experiments were used to develop a regression model for strength prediction. The model was validated using independent data from the literatures.

2. Experimental investigation

2.1 Materials

The materials used for preparation of mortars consisted of ordinary Portland cement (OPC), river sand, ground waste LDPE plastic and water. Figure 1 shows samples of the cement, sand, and LDPE fine aggregate used in the experiment. The cement used was OPC of grade CEM I 52.5 N with a specific gravity of 3.14 and of the chemical composition given in Table 1.

Air-dried natural river sand was used in the mortar mixtures. The river sand and LDPE materials conformed to medium sand classification (ASTM 2487 - 17). Table 2 gives the physical properties of sand and LDPE fine aggregate. Of particular interest is the low specific gravity of LDPE, being less than twice that of natural sand. Potable water was used for the mixing and curing of the mortars.

Figure 1: Samples of the mixture materials used to prepare LDPE mortars

Table 1: Chemical composition of CEM I 52.5 N Portland cement used

Constituents	Content (%)
Tricalcium silicate (C_3S)	57.64
Dicalcium silicate (C_2S)	20.98
Tricalcium aluminate (C_3A)	4.21
Tetracalcium aluminoferrite (C_4AF)	11.41
Gypsum	1.86
Potassium oxide (K_2O)	1.53
Sodium oxide (Na_2O)	0.10
Portlandite	0.50
Arcanite (K_2SO_4)	2.17
Loss on ignition (LOI)	2.50

Table 2: Physical properties of sand and LDPE fine aggregate

Material	Specific gravity	Compacted bulk density (kg/m^3)	Fineness modulus	Moisture content (%)
River sand	2.60	1695.00	2.50	2.04
LDPE fine aggregate	1.10	813.60	2.52	-

In preparing the LDPE fine aggregate, used water sachets made of LDPE plastic were collected, cleaned and cut into pieces. The sachets were melted at a temperature of 235^{o}C, then poured onto roofing sheets and left to solidify at normal temperatures. Afterwards, the solidified plastics were cut into rectangular pieces of about 30 × 50 mm, then ground into small particles using a metallic mortar and pestle. The ground plastic particles were then sieved through the 4.75 mm sieve size. The LDPE material passing the sieve was used as partial replacement for natural river sand in mortar mixtures. Figure 2 shows the waste LDPE plastic at various stages of preparation.

Figure 2: Waste LDPE plastic material at various stages of preparation.

2.2 Methods

2.2.1 Mortar mixtures

Mortar mixtures were prepared at 1 : 3 cement to sand ratio. The LDPE fine aggregate was incorporated as partial sand replacement in proportions of 0, 5, 10, 20, 30, 40, 50, and 60% by volume. Mixtures of different water /cement (w/c) ratios 0.45, 0.50, 0.55, and 0.60, were used in the experiment. The plain mortar was used as a control and denoted as Aq, where q is the w/c ratio. Mortars containing LDPE were denoted as Bg/q, where B stands for the word "batch" in mortars, g is the volume proportion of LDPE and q is the w/c ratio. Table 3 gives the mixture proportions of the mortars prepared.

2.2.2 Casting and curing of mortars

Fresh mortars were mixed using a small concrete mixer, then used to cast 50 mm cubes and 40 × 40 × 160 mm prisms. During casting, mortar was placed into moulds in two layers, each layer being compacted on a vibrating table. After casting, specimens were covered with a polyethylene sheet and stored at room temperature for 24 hours. The specimens were then demoulded and cured in water for 28 days at room temperature.

2.2.3 Testing of specimens

Five (5) specimens were used to obtain the average value of each test result. Compressive strength tests and density measurements were done on 50 mm cubes, in accordance with ASTM C 109 – 87 and BS 1881 – Part 114 (1983), respectively. Flexural strength was determined using 40 × 40 × 160 mm prisms as per ASTM C 348 (2013), while the water absorption tests were done in accordance with ASTM C 642 (2006).

Table 3: LDPE mortar mixtures

Mix number	Constituents of mortars containing LDPE plastic			
	Water (kg)	Cement (kg)	Sand (kg)	LDPE fine aggregate (kg)
A 0.45	0.162	0.360	1.080	0.000
A 0.50	0.180	0.360	1.080	0.000
A 0.55	0.198	0.360	1.080	0.000
A 0.60	0.216	0.360	1.080	0.000
B5/0.45	0.162	0.360	1.026	0.026
B5/0.50	0.180	0.360	1.026	0.026
B5/0.55	0.198	0.360	1.026	0.026
B5/0.60	0.216	0.360	1.026	0.026
B10/0.45	0.162	0.360	0.972	0.052
B10/0.50	0.180	0.360	0.972	0.052
B10/0.55	0.198	0.360	0.972	0.052
B10/0.60	0.216	0.360	0.972	0.052
B20/0.45	0.162	0.360	0.864	0.104
B20/0.50	0.180	0.360	0.864	0.104
B20/0.55	0.198	0.360	0.864	0.104
B20/0.60	0.216	0.360	0.864	0.104
B30/0.45	0.162	0.360	0.756	0.156
B30/0.50	0.180	0.360	0.756	0.156
B30/0.55	0.198	0.360	0.756	0.156
B30/0.60	0.216	0.360	0.756	0.156
B40/0.45	0.162	0.360	0.648	0.208
B40/0.50	0.180	0.360	0.648	0.208
B40/0.55	0.198	0.360	0.648	0.208
B40/0.60	0.216	0.360	0.648	0.208
B50/0.45	0.162	0.360	0.540	0.260
B50/0.50	0.180	0.360	0.540	0.260
B50/0.55	0.198	0.360	0.540	0.260
B50/0.60	0.216	0.360	0.540	0.260
B60/0.45	0.162	0.360	0.432	0.312
B60/0.50	0.180	0.360	0.432	0.312
B60/0.55	0.198	0.360	0.432	0.312
B60/0.60	0.216	0.360	0.432	0.312

* Density of sand = 1695.0 kg/m^3 and density of LDPE fine aggregate = 813.6 kg/m^3, therefore, weight of LDPE fine aggregate for an equivalent volume of sand (conversion factor) = 813.6/1695.0 = 0.48.

3. Results and discussion

3.1 Mechanical properties of mortars containing LDPE plastic

The strength results of LDPE mortars prepared at various w/c ratios, curing ages and LDPE contents, are given in Table 4 and Figure 3. It can be seen that strengths reduced as the w/c ratio increased regardless of the curing age and the LDPE content used. On average, compressive strength decreased by about 20% when the w/c ratio was increased from 0.45

to 0.60, irrespective of the LDPE proportion used. For instance, at 10% replacement of sand with LDPE fine aggregate, the 28-day compressive strength reduced from 40.6 MPa for 0.45 w/c to 32.8 MPa for 0.60 w/c, a reduction of 19.1%. It is also noticeable that flexural strength decreased as the w/c ratio increased. For example, when 30% of the sand was replaced with LDPE fine aggregate, flexural strength reduced from 4.25 MPa for 0.45 w/c to 3.59 MPa for 0.60 w/c, i.e. a decrease of about 16%.

The influence of curing age on compressive strength of the LDPE mortars is also evident in Figure 3. The figure shows that compressive strength increased with curing age, irrespective of the w/c ratio and LDPE content used. The results show that about 65% of the mortar strength developed during the first 7 days, while the remaining 35% developed after further 7 days of curing. Indeed, it can be seen that the strength curves at 14 and 28 days are closer to each other while the curves are further apart at the curing ages of 7 and 14 days. This pattern is evident in all the graphs of different w/c ratios.

It is interesting to observe that the strength curves show a two – stage, non - linear decrease in compressive strength as the LDPE content increases. At all w/c ratios, there is a relatively rapid (stage 1) decrease in compressive strengths with increase in LDPE contents up to 20%. Beyond 20% LDPE, the strength decrease is slower (stage 2) with further increase in LDPE content. At 20% LDPE, results gave 28-day compressive strength reductions of 43.8, 48.4, 44.6 and 46.8% for the 0.45, 0.50, 0.55 and 0.60 w/c mortars, respectively. At 60% LDPE, the strengths decreased by 81.6, 81.9, 83.1 and 82.6% for the 0.45, 0.50, 0.55 and 0.60 w/c mortars, respectively (Table 3). As such, the mortars retain a reasonably good strength at 20% LDPE content, maintaining about 55% the strength of control.

The foregoing findings of the present study are consistent with results in the literatures (Hannawi et al., 2010; Ghernouti and Rabehi, 2012; Wang and Meyer, 2012; Flomo, 2013), which showed major reductions in compressive or flexural strengths of mortars, upon incorporation of WP as aggregate into the mixtures. In their investigations, the compressive strength reductions for mortars containing 20% WP were up to 48%, which compares well with 43 to 47% obtained in the present study for 20% LDPE mortars.

The observed reductions in strengths of LDPE mortars investigated in the present study, is attributed to the smooth surfaces of WP particles, which weaken the adhesion between particles of LDPE plastic and cement paste at the interfacial transition zone.

Although strengths reduced as the content of LDPE increased, the mixtures satisfy the strength criteria for type M, S, N, and O masonry mortars, whose specified minimum compressive strengths are 17.2, 12.4, 5.2, and 2.4 MPa respectively (ASTM C 270 – 14). Type M mortar is prepared at 3 : 1 : 12 Portland cement to hydrated lime to sand. This class of masonry mortar is used for below grade load – bearing masonry works, and for chimneys, brick manholes etc. Type S mortar is a 2 : 1 : 9 cement to hydrated lime to sand mixture. It is used for below grade applications such as masonry foundation wall construction and for above grade works including the building of brick manholes, retaining walls, brick pavements, sewers, brick walkways. The specified mixture proportion for type N mortar is 1 : 1 : 6 cement to hydrated lime to sand. This mortar type is considered to be a general purpose masonry mortar for use in the above grade works of both the exterior and interior load - bearing installations. Finally, the type O mortar is a 1 : 2 : 9 cement to hydrated lime to sand mixture, proportioned to achieve at least 2.4 MPa compressive strength for use only in the above grade works under non - loading bearing conditions.

In the present study, the mortar mixtures of 0.55 /0.6 w/c incorporating 40, 50 and 60% LDPE gave 18.35 /16.05, 14.28 /12.42, 8.15 /7.91 MPa, which meet the strength criteria for masonry mortar types M, S, N respectively. Higher WP contents such as 80% LDPE would likely suit the criteria for type O masonry mortar.

Table 4: Strength and density test results of LDPE mortars

w/c ratio	LDPE fine aggregate content (%)	28-day compressive strength (MPa)	Compressive strength reduction 7 days (%)	14 days (%)	28 days (%)	28-day flexural strength (MPa)	Density at 28 days (kg/m^3)
0.45	0	55.38	0.0	0.0	0.0	5.05	2290
	5	46.76	10.3	14.9	15.6	5.28	2189
	10	40.58	22.2	25.7	26.7	5.19	2154
	20	31.10	42.6	43.5	43.8	4.80	2066
	30	24.49	54.7	56.0	55.8	4.25	1930
	40	21.34	62.1	62.5	61.5	3.84	1850
	50	17.14	67.1	68.5	69.1	3.60	1722
	60	10.20	81.8	81.7	81.6	3.24	1701
0.50	0	52.17	0.0	0.0	0.0	4.81	2274
	5	44.24	12.8	16.4	15.2	5.13	2174
	10	35.61	29.4	30.4	31.7	4.90	2141
	20	26.93	49.3	51.0	48.4	4.51	2018
	30	22.06	58.2	59.0	57.7	4.01	1903
	40	20.17	62.8	63.8	61.3	3.82	1839
	50	17.31	69.1	68.9	66.8	3.41	1709
	60	9.46	81.8	84.1	81.9	2.95	1690
0.55	0	48.21	0.0	0.0	0.0	4.52	2231
	5	40.16	11.5	15.8	16.7	4.81	2160
	10	35.03	22.5	25.7	27.3	4.51	2132
	20	26.73	43.5	44.2	44.6	4.22	2009
	30	21.19	55.1	56.3	56.0	3.84	1891
	40	18.35	62.0	62.4	61.9	3.53	1821
	50	14.28	68.8	68.9	70.4	3.18	1695
	60	8.15	83.8	83.7	83.1	2.68	1672
0.60	0	45.41	0.0	0.0	0.0	4.32	2216
	5	37.85	12.3	15.9	16.6	4.54	2149
	10	32.82	25.2	26.2	27.7	4.43	2117
	20	24.17	45.6	47.5	46.8	4.09	1998
	30	18.92	57.5	58.4	58.3	3.59	1872
	40	16.05	65.9	64.1	64.7	3.21	1801
	50	12.42	73.9	72.9	72.6	2.95	1679
	60	7.91	80.5	81.1	82.6	2.64	1655

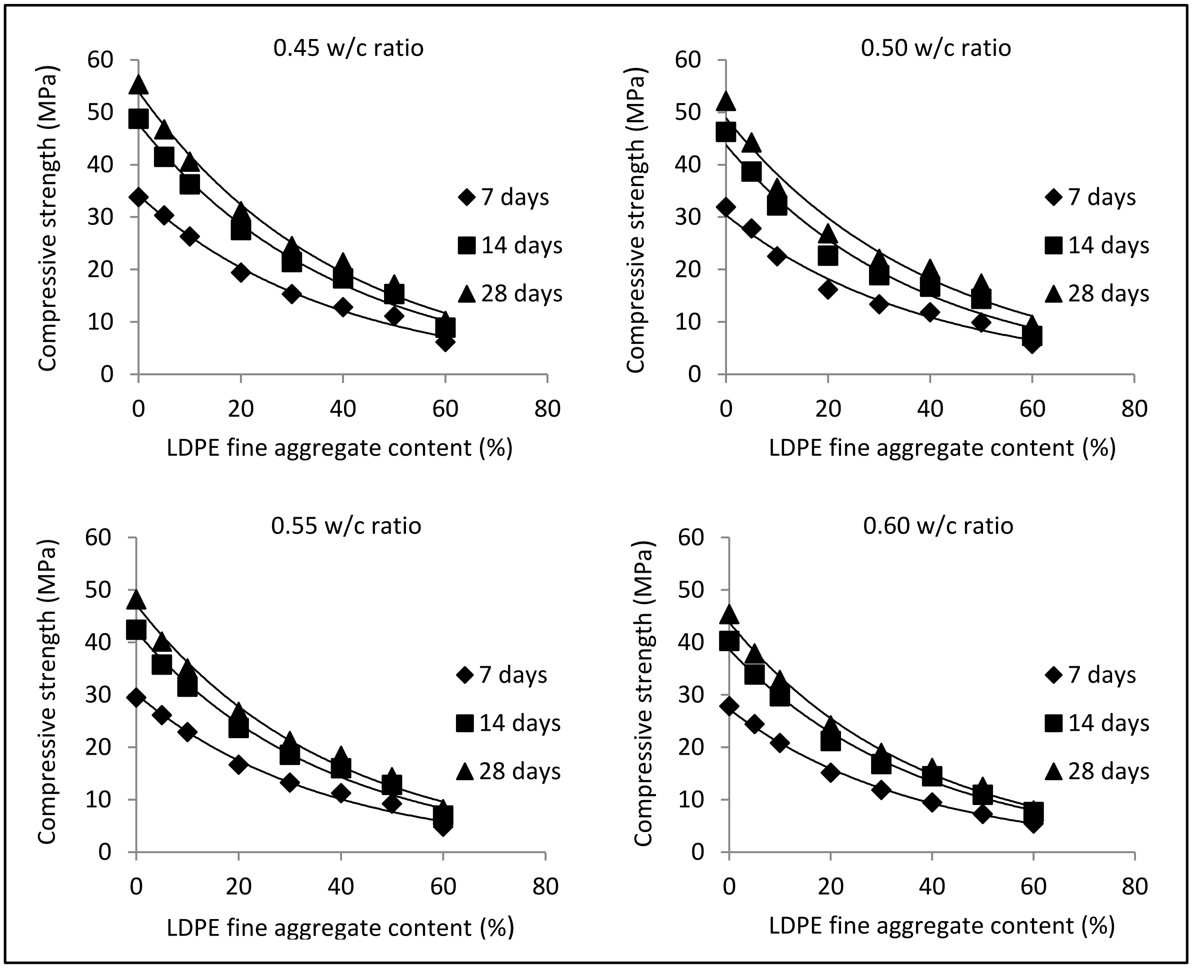

Figure 3: Effects of curing age and LDPE fine aggregate content on compressive strength of mortars prepared at various water/cement (w/c) ratios

3.2 Density of mortars containing LDPE plastic

Results giving the densities of LDPE mortars are also shown in Table 4. It is clear that density decreased as the LDPE content increased, as also seen in Figure 4. The reduction in density of the LDPE mortars was about 10% and 25% for mortars containing 20% and 50% LDPE fine aggregate. Generally, the percentage decrease in density was about one - half of the LDPE proportion in the mortar mixture. Hannawi et al. (2010) and Flomo (2013) reported similar density changes, giving 7% and 17% reductions for the respective mixtures containing 20% PET and 20% LDPE. These reductions in density are attributed to the lower specific gravities of the WP's used, being 1.24 and 1.04 for the PET and LDPE respectively.

In the present study, the observed reduction in density occurred due to the low specific gravity of the LDPE used, being 1.10 which is about 42% that of the natural sand (Table 2). As such, the use of LDPE mortars in lieu of cement - sand mortars for rendering, masonry bricks, joinery mortars etc, would significantly reduce the self - weight (dead loads) of the masonry elements such as walls, chimneys etc.

3.3 Water absorption of mortars containing LDPE plastic

Figure 5 shows the effect of LDPE fine aggregate content on water absorption of mortars prepared at the various w/c ratios. For 0.45 w/c ratio, the water absorption increased by 6.6, 11.5, and 24.2% for 10, 20 and 50% LDPE contents, respectively. Hannawi et al. (2010) also reported similar trends showing rise in water absorption with increase in the WP content.

The results in Figure 5 also show that water absorption increased with increase in w/c. For instance at 20% LDPE content, water absorption values were 2.71, 2.85, 3.01 and 3.14% for 0.45, 0.50, 0.55, 0.60 w/c respectively. The rise in water absorption of mortars with increase in LDPE content is attributed to the correspondingly higher void content of the mortars. Again, the relatively high porosity of LDPE mortars is a result of poor bond between LDPE particles and cement paste. Indeed, the relationship between LDPE content and increase in water absorption is linear as shown in Figure 5, giving a strong correlation indicated by R^2 of 0.97 to 0.99.

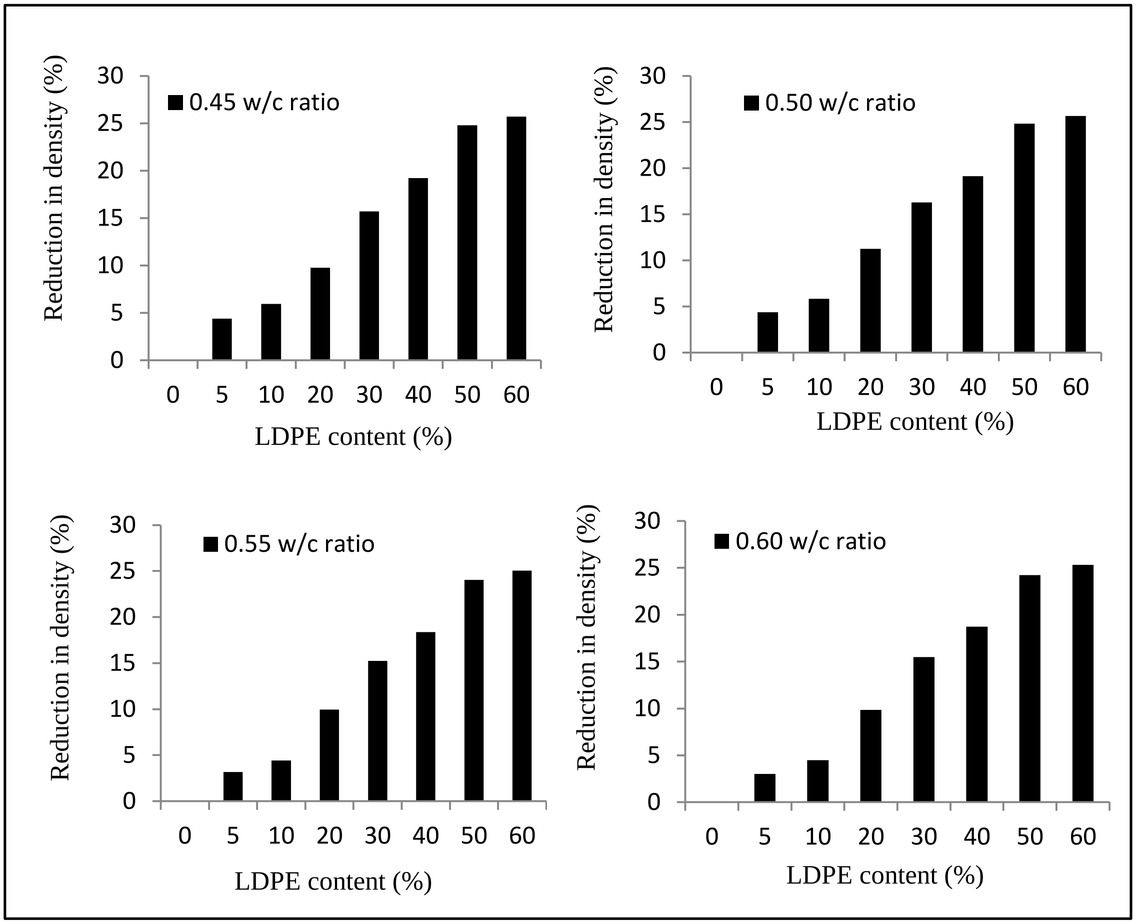

Figure 4: Reduction in density of mortar with increase in LDPE fine aggregate content for mortars of various water/cement (w/c) ratios

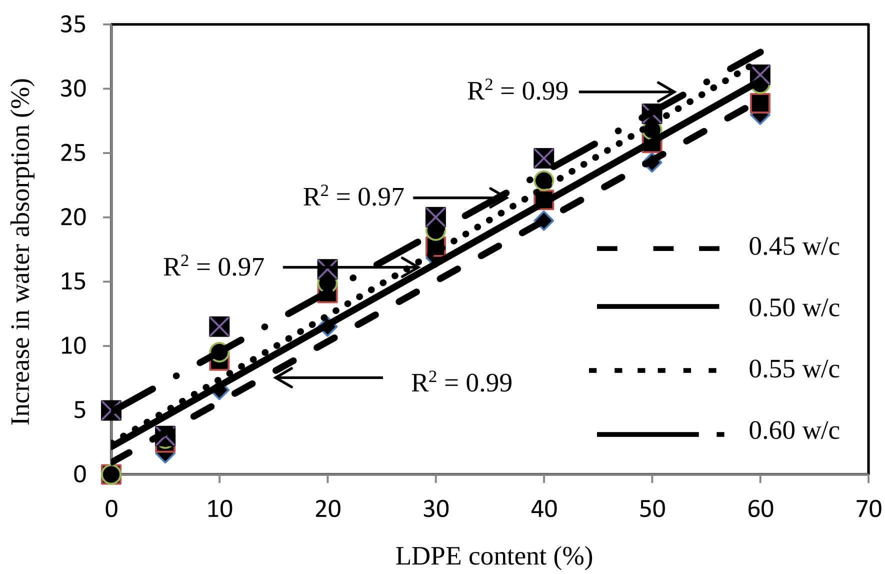

Figure 5: Linear relationship between LDPE content and water absorption for mortars of various water/cement (w/c) ratios

3.4 Relationship between compressive strength and density of mortars containing LDPE plastic

Figure 6 shows the relationship between compressive strength and density of LDPE mortars of various w/c ratios. It is clear that there is a strong linear correlation between compressive strength and density, giving the R^2 value of 0.96. From Figure 6, it is clear that the relationship between compressive strength (C_S) and density (d), is given by Equation (1).

$$C_S = 0.0689d - 106.17 \quad (1)$$

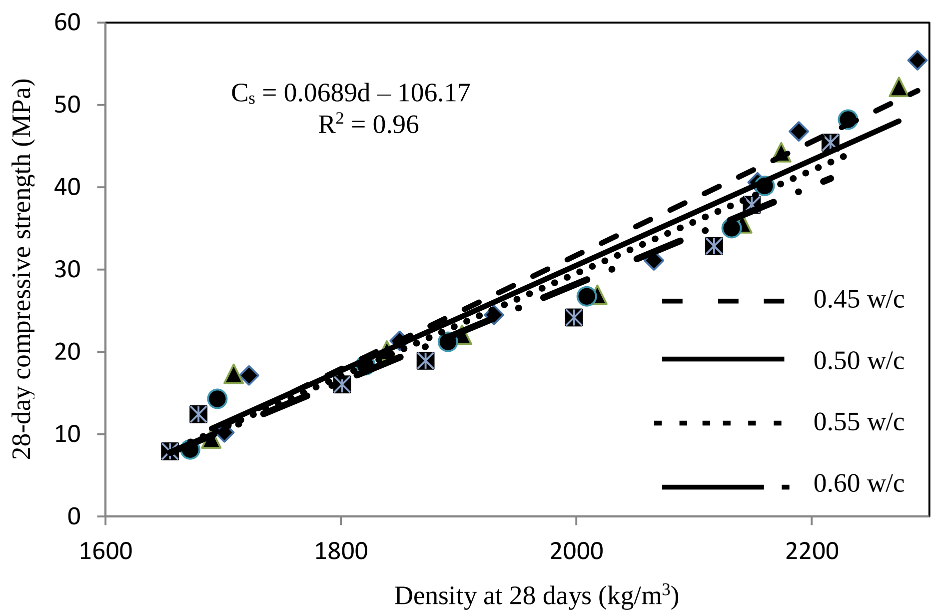

Figure 6: Relationship between compressive strength and density for LDPE mortars of various water /cement (w/c) ratios

4. Development of a model for predicting compressive strength of LDPE mortars

4.1 Multiple regression models

A strength prediction model was developed based on the experimental results presented in Table 4 and Figure 3. The multiple regression approach was employed for developing the prediction model using the Statistical Package for Social Sciences (SPSS), Version 16. Multiple regression analysis is by far the most widely used multivariate technique. It is employed to analyze the relationship between several independent variables and a single dependent variable (Hair et al., 1998). Thus multiple regression establishes the evidence that one or more independent variables (X_1, X_2, X_3, . . . , X_k) cause another dependent variable (Y) to change (Blaikie, 2003). In so doing, the analysis determines the relative magnitude of change contributed by each predictor variable. Furthermore, it also gives the proportion of the variance in the outcome, which can be explained by each predictor variable and/or their combined effect (Brace et al., 2006).

Using the classical linear regression approach, the relationship between the predicted outcome (Y_p) and the predictor variables (X_1, X_2, . . . , X_k) is defined as $Y_p = \alpha + \beta_1X_1 + \beta_2X_2 + \ldots \beta_kX_k + \varepsilon$, where α is a constant on the Y-axis, β_1 to β_k are coefficients of the independent variables (X_1 to X_k), and ε is the error term. In the present study, the independent variables were the w/c, LDPE content, and curing age, while the dependent variable was compressive strength of the LDPE mortar.

4.2 Model development and ANOVA

The *enter* selection technique in the SPSS was the mode used to conduct multiple regression. It is also known as *direct regression* or *simultaneous* regression. In this technique, all the predictor variables are tested at once. Table 5 presents results of the multiple regression analysis. The high value of R - squared ($R^2 = 0.89$), which is the coefficient of determination, indicates a strong correlation between the dependent variable (compressive strength) and the independent variables i.e. w/c ratio, LDPE content, and curing age. However, R^2 tends to somehow over - estimate the success of the model when applied to real data. As such, an adjusted R^2 value is calculated which takes into account the number of variables in the model and the number of observations upon which the model is based (Brace et al., 2006). Thus, the adjusted R^2 is useful as it gives an indication of the variance for compressive strength. In Table 5, the adjusted R^2 was 0.895, which is still very close to the non - adjusted R^2 of 0.898.

Using the adjusted R^2 and the analysis of variance (ANOVA) given in Table 6, the following conventional statistical report was generated: adjusted $R^2 = 89.5\%$, $F_{3,92} = 269.7$, $p < 0.001$. The p - value reported in Table 6 indicates the overall significance of the model. The emerged model indicates that 89.5% of the variation in compressive strength of LDPE mortars can be explained by the three variables comprising w/c ratio, LDPE content, and curing age. The B - column of Table 7 gives the coefficients of the independent variables in the regression equation. Table 7 also shows that the effects of w/c ratio, LDPE content, and curing age on the predicted compressive strengths are statistically significant, since $p < 0.001$. Subsequently, the model for predicting the compressive strength of LDPE mortars is derived as given in Equation (2).

$$C_S = -34.306w/c - 0.529pl + 0.459tm + 47.775 \qquad (2)$$

where C_s= compressive strength, w/c = water /cement ratio, pl = LDPE content, and tm = curing age.

The t - values and the respective p - values given in Table 7 indicate the significance of contributions from w/c ratio, LDPE content, and curing age in predicting compressive strength of the LDPE mortars. The t - values measure how strongly each variable influences the predicted compressive strength. Substituting Equation (1) of C_S into Equation (2), gives the expression in Equation (3), which can be used to predict the density of LDPE mortars.

$$d = -497.91w/c - 7.68pl + 6.66tm + 2234.33 \qquad (3)$$

where d = density of LDPE mortar

Table 5: Results of the multiple regression analysis

Model	R	R - squared	Adjusted R - squared	Std. error of the estimate
	.948[a]	.898	.895	4.03146

Predictors (constant): curing age, LDPE content, water/cement ratio

Table 6: Analysis of variance (ANOVA) showing the significance of the regression model

Model		Sum of squares	df	Mean squared	F	p - value
	Regression	13149.2	3	4383.1	269.7	.000[a]
	Residual	1495.2	92	16.3		
	Total	14644.4	95			

a. Predictors: constant, curing age, LDPE content, water/cement ratio

b. Dependent variable: compressive strength

Table 7: Coefficients of the independent variables in the regression equation

Model	Non - standardized coefficients		Standardized coefficients	t	p - value
	B	Std. error	Beta		
Constant (ε)	47.775	3.998		11.949	.000
Water/cement ratio (X_1)	-34.306	7.360	-.155	-4.661	.000
LDPE content (X_2)	-.529	.020	-.877	-26.314	.000
Curing age (X_3)	.459	.047	.325	9.741	.000

Dependent variable (Y): compressive strength

4.3 Validation

The model developed in the present study was applied to data taken from past researches (Hannawi et al., 2010; Ghernouti and Rabehi, 2012; Wang and Meyer, 2012; Flomo, 2013) that had similar mixtures as those used in the current study, but employed different types of plastics comprising PET, HIPS and LDPE. Hannawi et al. (2010) used PET plastic, cement /sand ratio of 1 : 3, 0.5 w/c ratio and Portland cement grade CEM I 52.5. Wang and Meyer (2012) employed HIPS plastic, cement /sand ratio of 1 : 3, 0.55 w/c ratio and Type I general purpose Portland cement of ASTM C 150 /150M – 09, while Ghernouti and Rabehi (2012) used WPB plastic, cement /sand ratio of 1 : 3, 0.5 w/c ratio and cement grade CEM II 32.5. A study by Flomo (2013) involved LDPE mortar mixtures cast using Dangote 3X cement 42.5R and prepared at a cement /sand ratio of 1 : 3 with 0.5 w/c ratio. By comparing the experimental results taken from the literatures to the model's predicted values, it can be seen in Table 8 that the model was effective in correctly predicting the compressive strengths and densities of mortars containing different types of plastic. Figure 7 shows that there is a strong correlation between the predicted results and the actual values measured in the experiment (Hannawi et al., 2010; Ghernouti and Rabehi, 2012; Wang and Meyer, 2012; Flomo 2013).

The ratios of actual values (AV) to predicted values (PV) of compressive strengths and densities are also given in Table 8. It can be seen that the AV/PV values for compressive strength fall within 0.9 to 1.3, averaging 1.07 for all data comprising the results of PET, HIPS, WPB and LDPE mortars. The AV/PV values for density are all approximately 0.9 to 1.0. These ratios show a very close agreement between experimental results and the predicted values of compressive strengths and densities. Also given in Table 8 are residuals showing that the actual and predicted strength results are mostly within ±6 MPa. The coefficient of variation of errors (CVE) was determined to be 13%, which shows a very good agreement between the model's predictions and experimental results. CVE values of 20 to 40% are generally recognised and accepted for standardized models (Bazant and Baweja, 1995; Lifecon, 2003; Ekolu, 2018).

Table 8: Comparison of compressive strength and density data taken from past researches versus the model's predictions

Author	Types of plastic	Content of plastic (%)	28-day compressive strength (MPa)				Density of 28 days (kg/m^3)		
			Actual value (AV)	Predicted value (PV)	AV/PV (ratio)	Residual (AV-PV)	Actual value (AV)	Predicted value (PV)	AV/PV (ratio)
Hannawi et al. (2010)	PET	0	52.00	43.47	1.20	8.53	2173	2172	1.00
		3	45.00	41.89	1.07	3.11	2154	2149	1.00
		10	38.01	38.18	0.99	-0.17	2088	2095	0.99
		20	29.69	32.89	0.90	-3.20	2023	2018	1.00
		50	17.00	17.02	1.00	-0.02	1755	1788	0.98
Wang and Meyer (2012)	HIPS	0	37.50	41.76	0.90	-4.26	-	-	-
		3	-	-	-	-	-	-	-
		10	34.01	36.47	0.93	-2.46	-	-	-
		20	30.71	31.18	0.98	-0.47	-	-	-
		50	17.05	15.31	1.11	1.74	-	-	-
Ghernouti and Rabehi (2012)	WPB	0	45.00	43.47	1.04	1.53	-	-	-
		10	36.00	38.18	0.94	-2.18	-	-	-
		20	33.00	32.89	1.00	0.11	-	-	-
		30	29.00	27.60	1.05	1.40	-	-	-
		40	25.00	22.31	1.12	2.69	-	-	-
Flomo (2013)	LDPE	0	50.40	43.47	1.16	6.93	2266	2172	1..04
		5	46.22	40.83	1.13	5.39	2080	2133	0.98
		10	44.34	38.18	1.16	6.16	1992	2095	0.95
		15	43.03	35.54	1.21	7.49	1968	2056	0.96
		20	42.19	32.89	1.28	9.30	1886	2018	0.93
		30	30.23	27.60	1.10	2.63	1832	1941	0.94
		40	26.33	22.31	1.18	4.02	1613	1865	0.86

*PET = polyethylene terephthalate, HIPS = high impact polystyrene, WPB = waste plastic bags, LDPE = low density polyethylene.

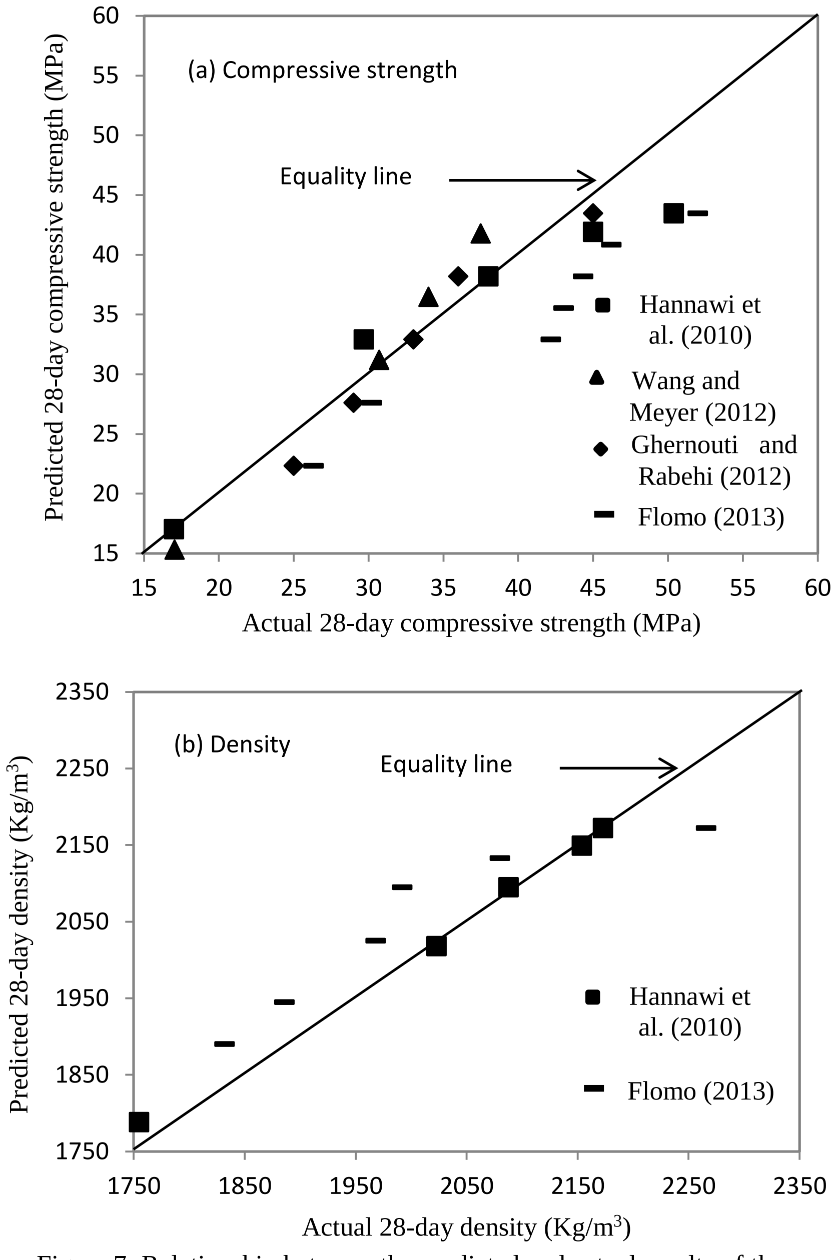

Figure 7: Relationship between the predicted and actual results of the mortar containing PET, HIPS, WPB and LDPE plastics (a) compressive strength, (b) density

5. Conclusions

The physical and mechanical properties of mortars containing LDPE were adversely affected when the waste plastic was used as a partial replacement for sand. Data of other types of plastics comprising polyethylene terephthalate (PET) and high impact polystyrene (HIPS), were employed in validating the strength prediction model proposed in the present study. From the findings, the following specific conclusions have been reached.

(a) There was a decrease in density, compressive strength, and flexural strength with increase in the proportion of waste LDPE plastic in mortar. Also, water absorption of mortar increased as the content of waste plastic increased. At 20% LDPE content, there was 10% reduction in density, 11.5% increase in water absorption, while the mortar strength was about 55% that of control.

(b) Incorporation of 50 to 60% LDPE as fine aggregate into the mortar mixtures satisfied the strength criteria for type M, S, N, O masonry mortars.

(c) LDPE mortars have significantly lower self - weight relative to the normal cement - sand mortars. Use of LDPE mortars in masonry would reduce the dead loads of structural masonry elements.

(d) Although the proposed model was developed based on LDPE data, it was interestingly found to apply to other types of plastics including PET and HIPS, provided similar mixture parameters comprising the water /cement ratio, proportion of the waste plastic and curing age, are employed. Statistical validation showed the effects of these mixture factors to be statistically significant ($p < 0.001$). The small coefficient of variation of errors determined to be 13% for all the data employed in the validation, is well within the acceptable range of 20 to 40% for standardized prediction models. Accordingly, the model showed good prediction accuracy when applied to independent experimental data taken from the literatures.

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