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Performance of dry cast concrete blocks containing waste glass powder or polyethylene aggregates

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ABSTRACT

Dry-cast concrete blocks are a popular building material; however, to improve the economic and environmental sustainability of this industry, its dependence on natural aggregate and Portland cement needs to be reduced. To further this goal, blocks with up to 25% of the cement replaced with waste glass powder (WGP) or up to 15% of the sand replaced with high density polyethylene (HDPE) or low density polyethylene (LDPE) polymer pellets were produced in an industrial plant. The physical, mechanical and durability properties of the individual blocks and the mechanical properties of the block assemblages were tested. Based on statistical analyses, the blocks with 10% WGP as cement replacement performed similarly to the control blocks. The block properties were sensitive to the use of either type of polyethylene aggregate, which resulted in a decrease in strength and an increase in water absorption. Acceptable performance was achieved when 3–6% of the sand was substituted with polymer pellets.

1. Introduction

Masonry construction, which is a build-up of block units and mortar joints, has been a popular technique for millennia because it allows for quick, efficient, durable and economic construction. The continuation of this historic trend is possible provided that the masonry industry remains economically and environmentally sustainable. To meet this objective, the masonry industry needs to explore alternative methods that allow for the reduction of (a) non-renewable materials, (b) energy used in the production of the concrete block units, and (c) labour cost, while maintaining the same performance requirements. This study investigates the use of waste materials as alternatives to aggregate and cement in the production of concrete block units.

Waste materials as partial replacement of natural aggregates in concrete, including construction and demolition (C&D) waste [1], glass [2–5] and polymers [6–8], have been studied. A review of the literature has revealed that C&D waste and glass as partial aggregate replacement have been studied extensively in comparison to polymer waste. The results show on average a decrease in compressive strength and an increase in water absorption when C&D waste and glass are added as aggregate replacements. Furthermore, for glass, the development of alkali–silica reaction (ASR) gel remains a major concern [2–5,9]. With regard to polymers, a significant portion of recyclable polymers ends up in landfill due to the low cost of producing them from virgin material, mixing of polymer types during recycling, or contamination with other materials [10]. Ismail and Al-Hashmi [11] studied the effects of replacing fine aggregate, namely sand with polymer aggregate, concluding that a 20% sand replacement with waste polyethylene and polystyrene aggregate resulted in a 7% reduction in the density of the concrete [11]. Significant reduction in the compressive strength of concrete has also been observed [6–8]. Ghaly and Gill [6] reported a 29% decrease in compressive strength when 15% of the coarse aggregate was replaced by post-consumer waste polymer aggregate at a water to cement ratio (w/c) of 0.42; however, they also observed a more ductile failure mechanism. It should be noted that most of the research into the use of polymer aggregate has been on polyethylene terephthalate, commonly known as PET; the polymer used to manufacture plastic bottles [10]. Other polymers, such as low and high density polyethylene, which possess different properties, have not been thoroughly studied in this application.

Silica fume, fly ash and ground granulated blast furnace slag, which were once considered waste materials, are now used in the production of concrete and concrete blocks as supplementary cementitious material (SCM). Due to their pozzolanic properties, the partial cement replacement with these mineral admixtures

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has yielded improved physical, mechanical and durability properties, as well as improved the economic and environmental sustainability of the concrete industry [12]. Other researchers have studied the use of waste glass powder (WGP) as a SCM because of its high silica content [13–15]. Glass, which is an amorphous material, has been shown to exhibit pozzolanic properties when ground finer than 75 μm, [13,15,16]. Use of up to 30% WGP as cement replacement has yielded minor reduction in compressive strength when compared to the control at 28-days and comparable strength to the control at 90-days [13,14]. A recent study has shown that WGP at up to 10% cement replacement in concrete yields similar results to fly ash at the same replacement level after 90-days [17]. The main deterring factor for using WGP as cement replacement and/or glass particles as aggregate replacement remains ASR. However, data reported in the literature indicates that ASR due to WGP is nonexistent when the particle size is less than 45 μm [16].

The objective of the investigation is to study the effects of using post-consumer waste materials on the performance and production of dry-cast concrete masonry blocks [18]. WGP was used as cement replacement and, HDPE and LDPE polymer pellets were used as sand replacement. The blocks were produced in an industrial plant. The performance of the blocks was investigated through density, compressive strength, elastic modulus and bond strength analyses representing the physical and mechanical characteristics of the unit block and prism assemblage, and through water absorption, initial rate of absorption (IRA), and ASR analyses representing the durability of the concrete block.

2. Experimental investigation

2.1. Materials

Cement conforming to CSA type 30 HE [19], and WGP, which was obtained from a post-consumer waste source, were used as cementitious materials in the concrete mixtures. The chemical characteristics of the cement and WGP are given in Table 1. The maximum nominal particle size of WGP was 36 μm and the moisture content was less than 0.1%.

Crushed limestone with a maximum nominal size of 5 mm was used as the coarse aggregate. Siliceous sand, with a fineness modulus (FM) of 3.2 and particle size distribution given in Fig. 1 was used as fine aggregate. Low density polyethylene (LDPE) pellets, high density polyethylene (HDPE) pellets, and grafted HDPE pellets were also used as fine aggregate. The particle size distribution of the pellets is shown in Fig. 1. The FM for the LDPE, HDPE and grafted HDPE was 3.9, 4.1 and 3.6, respectively. These results indicate that the polymer aggregates have particles that are slightly coarser than those of the sand. The contact angle of the three polymers, given in Table 2, indicates that the polymers are hydrophobic. Two distinct contact angles were measured for the grafted HDPE indicating that the side chains are structurally distinct from the main chain.

Table 1
Chemical composition of cement and WGP.

Constituents (% by mass)	CSA type HE cement	WGP
SiO_2	20.89	70.59
Al_2O_3	6.09	2.03
Fe_2O_3	2.31	0.53
CaO	65.04	10.52
MgO	2.57	0.94
K_2O	0.88	0.52
Na_2O	0.22	13.37
TiO_2	0.29	0.06
MnO	0.05	0.02
P_2O_5	0.12	0.02
Cr_2O_3	0.00	0.06
LOI	1.53	1.25

2.2. Mixture proportions

The proportions of the control block mixture were based on the standard mixture used at the industrial plant. The cement content was partially replaced with WGP at 10% and 25% by weight. Sand was replaced, by volume, at 3%, 6%, 9% and 15% with LDPE and HDPE. The 15% replacement of the total sand was limited by the hydrophobic nature of polyethylene (PE) while the 3% grafted HDPE replacement of sand was limited by the supply. The concrete mixture proportions of the blocks are given in Table 3. The mass of coarse aggregate was 522 kg per batch for all 12 mixtures. The water to binder ratio (w/b) of the mixtures ranged between 0.23 and 0.34 with the corresponding average and coefficient of variance equal to 0.26 and 10%, respectively.

Structural type S mortar was used to build the prisms. The mortar mixture consisted of CSA type 10 GU cement [19], hydrated lime, sand and water. The mixture proportions are given in Table 4.

2.3. Production

2.3.1. Block

The blocks were produced in an industrial dry-cast block making plant. The mixing procedure was in accordance with the following steps: (1a) fine and coarse aggregates were added to the mixer and mixed for 20 s; (1b) for the blocks with polymer aggregate, the PE aggregate was added next and mixed for 20 s; (2a) cement was added and mixed for an additional 20 s; (2b) for the blocks containing WGP, WGP was added with the cement; (3) water was added to achieve the desired consistency. The total mixing time and amount of water added is given in Table 5.

The mixture was placed into steel moulds and consolidated. Because it is a dry-cast production, the uncured blocks were de-moulded immediately following consolidation and visually inspected. The geometry of the WGP blocks and the blocks containing 3% or 6% PE polymer aggregate was stable and no visual difference was observed between them and the control. Some of the blocks containing higher percentages of PE polymer aggregate were found to have cracks in the webs upon de-moulding. This is most likely caused by the repulsive forces generated between the hydrophobic polymer aggregates and water. For the blocks with 15% PE polymer aggregate, the change in their length and width was 1 mm–2 mm in comparison to the control blocks, the expansion was large enough to crack some of the blocks.

The blocks were steam cured for 12 h. One month after production, the blocks were shipped to the McMaster University Applied Dynamics Laboratory for testing.

2.3.2. Prism

Prisms were built by a certified mason to test the compressive strength and bond strength of the block assemblage. Accordingly, prisms four units high and one unit wide were constructed in a running bond pattern and stack pattern. The mortar joints were 10 mm thick with face shell bedding and a concave profile.

2.4. Test program

2.4.1. Physical and mechanical characteristics

The density of the blocks was determined in accordance with ASTM C140 [21]. The reported values represent the average of the results of five blocks. The compressive strength of the blocks was tested following the procedure outlined by ASTM C140 [21]. Five blocks were tested per mixture and were capped according

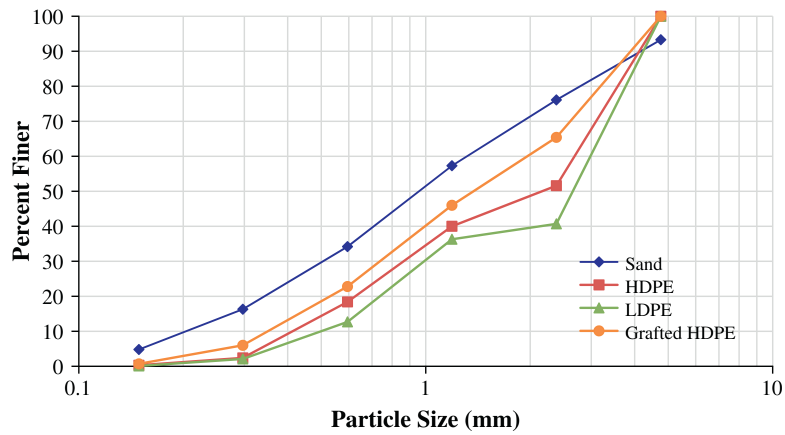

Fig. 1. Particle size distribution of fine aggregate.

Table 2
Polyethylene contact angle.

Polymer	Mean (°)
LDPE	95.8 ± 1.2
HDPE	94.7 ± 2.9
Grafted HDPE	94.5 ± 5.8 or 67.7 ± 4.3

to ASTM C1552 [22]. The elastic modulus was measured on four of the five blocks tested for compression. The elastic modulus was determined from displacement measurements across a 70 mm gauge length. The range used in the calculation of the modulus was always within the elastic response of the material corresponding to 5% and 50% of the ultimate block strength.

The compressive strength of the prisms was tested following CSA S304.1 [23] and ASTM C1314 [24]. Concurrently, displacements were measured using four linear potentiometers across a 610 mm gauge length on each prism, and were subsequently used to calculate the prism's elastic modulus. The modulus, which was always in the elastic range of the material, was the secant modulus within 5% and 33% of the prism's ultimate compressive strength [23]. The reported strength and modulus results are the average values of five prisms for each block type.

The bond wrench test was used to determine the masonry flexural tensile bond strength [23,25]. Two four-block high stacked prisms, comprised of three joints each, were used to measure the bond strength for each block type. In this investigation, six joints were tested which is less than the minimum number of 15 joints stipulated in the standard.

2.4.2. Durability characteristics

The block's water absorption was measured in accordance with ASTM C140 [21]. The reported values are an average of the results obtained from five randomly selected blocks. The initial rate of absorption (IRA), which is not a standard test for concrete block, was used to evaluate the effects of the WPG and PE additions on the water uptake of the blocks. The procedure stipulated for brick masonry was followed [26].

The ASTM C1260 [27] mortar bar test was adapted to test for ASR expansion. The mortar bar, which is the sample required by the

Table 4
CSA type S mortar composition.

	Cement	Hydrated lime	Sand
Mass (kg)	7.6	1.5	27
Density (kg/m^3)*	1505	640	1280
Proportions (by volume cement)	1	0.46	4.16

* Density values are taken from CSA 179 [20].

Table 5
Water added and total mixing time.

Block	Water added (L)	Mixing time (s)
C	32	135
G10	32	130
G25	32	130
LP3	30	126
LP6	30	110
LP9	30	110
LP15	40	110
HP3	30	126
HP6	30	110
HP9	30	105
HP15	29	105
GP3	27	125

Table 3
Mixture proportions of blocks per batch.

Label	Block designation	Cement (kg)	Sand (kg)	LDPE (kg)	HDPE (kg)	Grafted (kg)	WGP (kg)
Control	C	118	841	0	0	0	0
10% WGP	G10	106	841	0	0	0	12
25% WGP	G25	88	841	0	0	0	29
3% LDPE	LP3	118	816	16	0	0	0
6% LDPE	LP6	118	790	31.5	0	0	0
9% LDPE	LP9	118	765	47	0	0	0
15% LDPE	LP15	118	715	79	0	0	0
3% HDPE	HP3	118	816	0	16	0	0
6% HDPE	HP6	118	790	0	31.5	0	0
9% HDPE	HP9	118	765	0	47	0	0
15% HDPE	HP15	118	715	0	79	0	0
3% Grafted	GP3	118	816	0	0	16	0

standard, was replaced with a cut-out portion of the concrete block. The sample size was 285 mm long by 33 mm wide and 33 mm thick. Although the standard stipulates a bar thickness of 25 mm, the block face shell thickness of 33 mm was used. Therefore, the paste content and size of the tested samples did not conform to the standard. However, the accelerated test was used to study the effects of the mixtures composition on the samples' expansion. The mixtures that were subjected to the ASR accelerated test were the control, the 10% WGP blocks, the 25% WGP blocks and the 15% LDPE blocks. Three samples were prepared and tested for these four block types and the average is reported. Expansion was measured using a DEMEC with a 25 cm gauge length.

3. Results and discussion

A summary of the submersion test results for all the blocks is given in Table 6. The mechanical properties of the blocks are presented in Figs. 2–4. The mechanical properties of the prisms are shown in Figs. 5–7. Fig. 8 displays the expansion according to the ASR test method. All the results were evaluated using the statistical student *t*-test with a 95% confidence interval [28].

3.1. WGP as cement replacement

3.1.1. Block physical properties

For the mixtures containing WGP, the statistical analysis revealed no significant difference between the control density and that of blocks containing 10% WGP. The density was slightly lower for blocks containing 25% WGP. For the water absorption, no significant difference was noted between the control blocks and blocks containing 10% WGP, but a slightly higher absorption was observed for blocks containing 25% WGP. The average absorption of the blocks containing 25% WGP was 12% greater than those of the control. These results are consistent with the data reported by Taha and Nounu [29]. They attributed the increase in water absorption to a change in the hydration products and microstructure of the concrete when WGP is added. Measurements of the IRA of the blocks revealed a lower value for the control in comparison to blocks containing 10% WGP and 25% WGP. These results, which are in agreement with those obtained for water absorption, indicate a change in the capillary pore structure due to the addition of WGP.

3.1.2. Block mechanical properties

The compressive strength of the concrete blocks was tested at 4, 160 and 365 days. The strength development of the blocks with WGP is shown in Fig. 2. The results reveal that the 4-day compressive strength of the control blocks and blocks containing 10% and 25% WGP exceeded the minimum strength of 12 MPa required by the production plant. The compressive strength of the blocks containing 25% WGP is statistically lower than that of the control blocks at all ages. The compressive strength of the blocks containing 10% WGP is statistically lower than that of the control at 160-days, and statistically the same at 4 and 365 days. The increase in strength of the 10% WGP blocks from 160 to 365 days indicates a pozzolanic reaction. The trend is similar to that reported by Shao et al. [13] and Shayan and Xu [14]. For the blocks containing WGP, three observations can be made: the degree of WGP hydration decreases when the amount of WGP increases from 10% to 25%; the pozzolanic reaction rate for the 10% WGP blocks and 25% WGP blocks is similar between 4 and 160 days; and the pozzolanic reaction continues at a lower rate for the 10% WGP blocks. However, no increase in strength was measured for the 25% WGP blocks from 160 to 365 days.

Table 6
Block properties from submersion tests.

Block	Density (kg/m^3)	Water absorption (%)	IRA (kg/m^2/min)
C	2165 ± 12	5.0 ± 0.1	0.5 ± 0.1
G10	2146 ± 16	5.2 ± 0.3	0.7 ± 0.2
G25	2140 ± 4	5.6 ± 0.3	0.7 ± 0.1
LP3	2098 ± 30	5.2 ± 0.2	0.8 ± 0.1
LP6	2016 ± 8	7.1 ± 0.3	2.2 ± 0.4
LP9	1960 ± 6	7.3 ± 0.2	2.4 ± 0.4
LP15	1842 ± 12	8.1 ± 0.6	2.6 ± 0.5
HP3	2097 ± 10	5.4 ± 0.2	0.7 ± 0.1
HP6	2022 ± 11	6.9 ± 0.3	2.3 ± 0.4
HP9	1930 ± 22	7.7 ± 0.1	2.1 ± 0.2
HP15	1825 ± 18	10.4 ± 0.5	6.0 ± 0.4
GP3	2076 ± 14	6.2 ± 0.3	1.1 ± 0.2

The elastic modulus of the blocks is shown in Fig. 4. The elastic modulus of blocks containing 10% and 25% WGP is statistically equal to one another, but slightly lower than the control.

3.1.3. Block durability

The equivalent alkali content of WGP is approximately 14%, which, according to the literature, is sufficient to promote ASR [14]. It was also reported that glass finer than 45 μm is unlikely to produce ASR expansion [16]. Given these uncertainties, the control and blocks containing WGP were tested and the measured strains are plotted in Fig. 8. Samples containing 15% LDPE were tested for comparison. Statistical analysis of the 14-day strains reveals that the samples containing 15% LDPE and 25% WGP have higher expansion than the control and samples containing 10% WGP have lower expansion than the control. The latter concur with the results reported by Shi and Zheng [30] even though the testing protocol did not conform to the standard. The expansions, after 30-day exposure, were found to be less than the 1000 μm/m 14-day expansion criterion set by the standard to identify materials that are susceptible to ASR. Microscopic analysis of the samples containing WGP revealed no ASR present. Therefore, the recorded expansions cannot be attributed to ASR, which is the objective of the test, but rather to anomalies associated with the accelerated test [31].

3.1.4. Prism mechanical properties

The compressive strength of the prisms is shown in Fig. 5 along with the corresponding mortar strength. Statistically, it was found that there is no significant difference between the compressive strength of the control prisms and that of the 10% and 25% WGP prisms. The failure mechanism of the prisms, which is shown in Fig. 9a, is typical splitting through the webs. Also, the elastic modulus of the prisms, shown Fig. 6, is found to have no significant difference.

The bond wrench test results are shown in Fig. 7. Statistically, there is no significant difference between the bond strengths of the control, 10% WGP and 25% WGP blocks. Bond strengths are found to correlate with IRA, thus confirming what has been reported in the literature [32].

3.1.5. General discussion of WGP results

While the addition of WGP has some effect on the concrete block properties tested, there is no indication that 10% cement replacement with WGP will have any negative effect on the performance of the blocks. Blocks with up to 25% cement replaced with WGP are also adequate as long as slower strength development is tolerable, as well as a small increase in the water absorption properties. The early strength of the blocks meets and exceeds the requirements of the block manufactures so there is no indication that these blocks would require different manufacturing procedures than the control blocks. The average strength of the 25% WGP blocks is 16% lower than the control which is less strength loss than would be expected if the cement was replaced with an inert filler material. In the case of the prisms, there was no statistical indication that using blocks with up to 25% replacement will affect their performance.

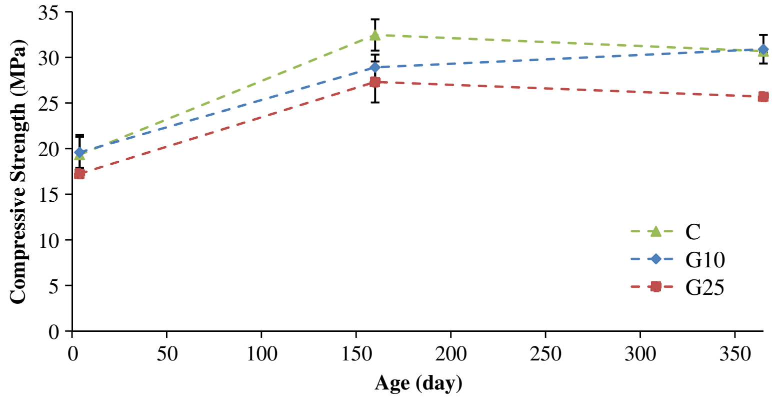

Fig. 2. Compressive strength development for blocks with WGP.

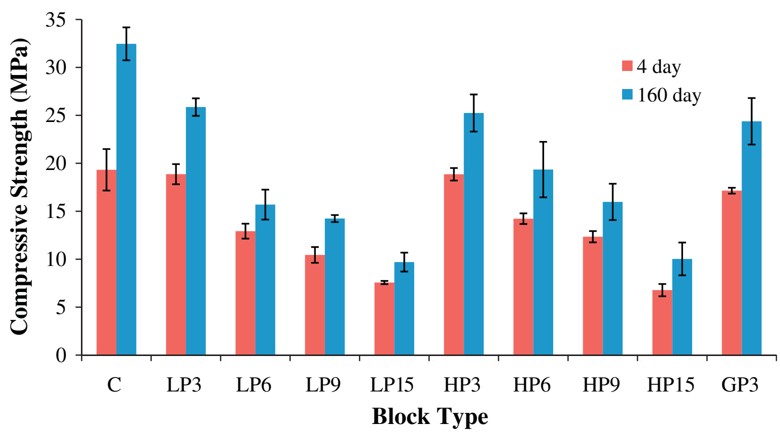

Fig. 3. Compressive strength of blocks with polymer aggregate.

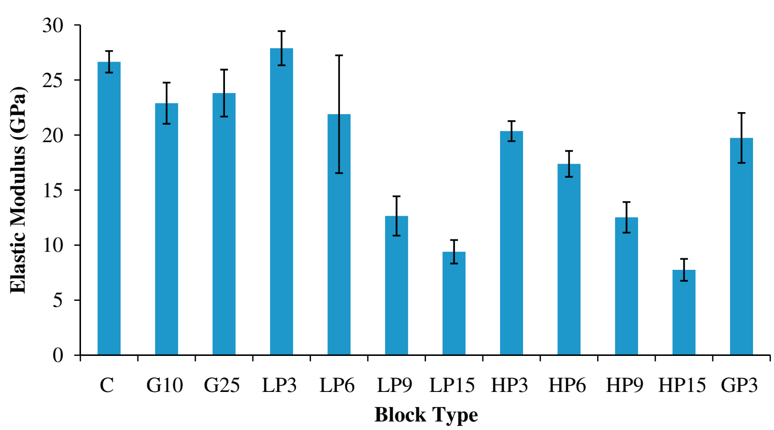

Fig. 4. Elastic modulus of blocks.

The presence of ASR was not detected in any of the blocks with WGP tested. However, its formation depends on the type of glass, the glass particle size, the cement alkalinity and the reactivity of the natural aggregate. This complex relationship makes it difficult to predict the occurrence of ASR if one of these factors is changed.

3.2. PE as fine aggregate replacement

3.2.1. Block physical properties

The addition of PE as sand replacement has a significant effect on the density of the blocks as shown in Table 6. The decrease in the density of the blocks with an increase in HDPE and LDPE content is due to the difference in the density of PE and sand. The density of sand, LDPE, and HDPE is 1600 kg/m^3, 920 kg/m^3 and 950 kg/m^3 [33], respectively. According to CSA A165.1 [34], blocks can be classified low density masonry units if their density is less than 1700 kg/m^3. Although this was not achieved even for block containing 15% PE, the reduction in the density of the blocks will improve the mason's productivity and reduce the dead weight of the structure.

Table 6 shows an increase in the water absorption and IRA of the blocks when the percentage of PE increases. Statistical analysis

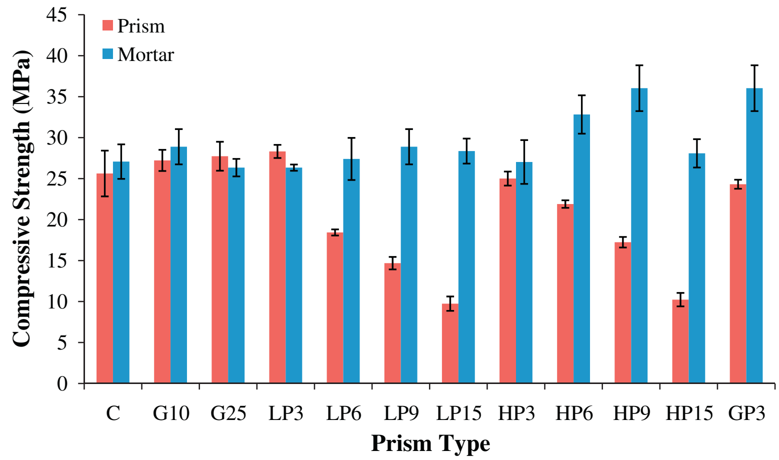

Fig. 5. Prism compressive strength and corresponding mortar strength.

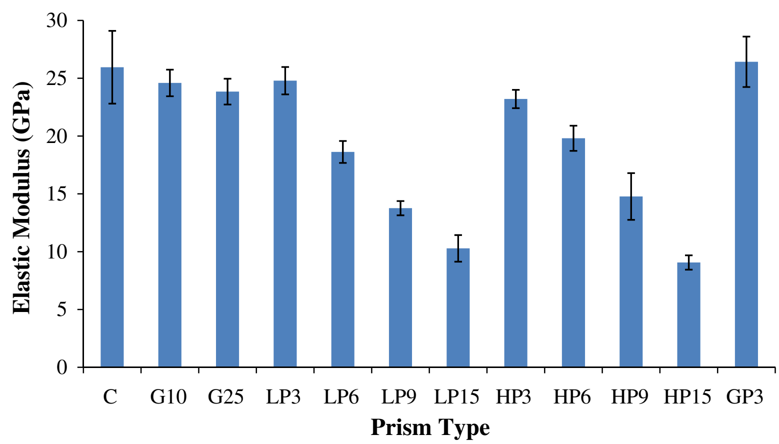

Fig. 6. Elastic modulus of prisms.

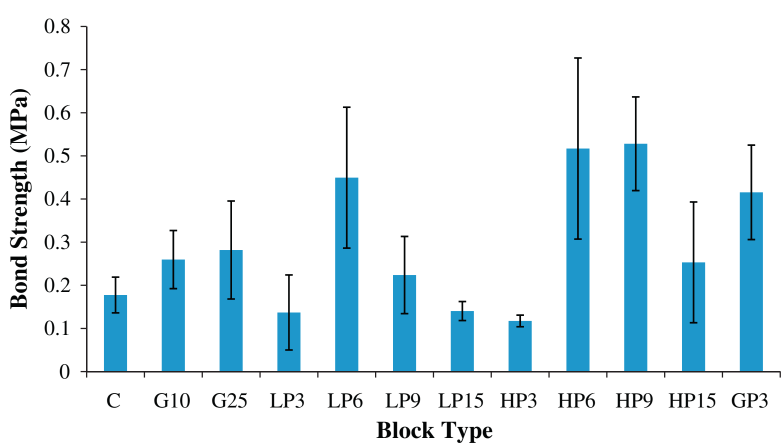

Fig. 7. Bond wrench results.

of the results revealed that the control, 3% LDPE and 3% HDPE blocks have no significant difference in their water absorption values. However, the replacement of 3% sand with grafted HDPE resulted in a 24% increase in the water absorption values in comparison to the control. At the higher replacement levels of 6%, 9% and 15%, the absorption increased by 41%, 46% and 62%, respectively, for the LDPE compared to the control. A similar trend is observed for the blocks containing HDPE. The exception was for the blocks containing 15% HDPE, where the absorption was significantly higher than the values recorded for the blocks containing 15% LDPE, as well as the control. The increase in water absorption is attributed to the increase in the porosity of the blocks containing PE and

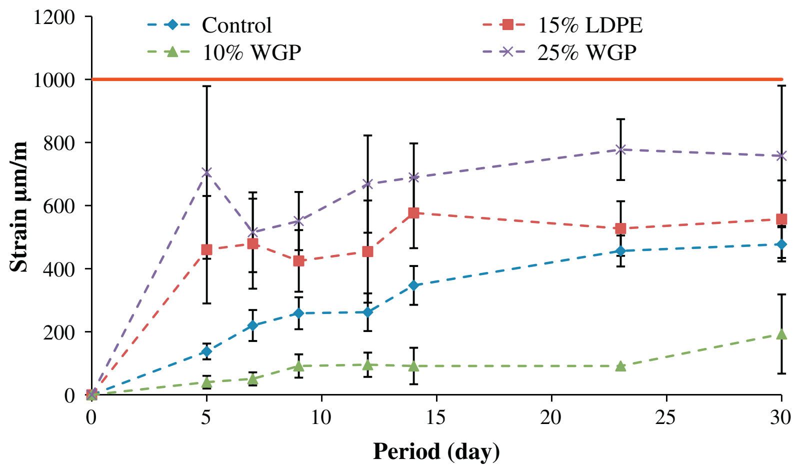

Fig. 8. Expansion following ASR test standard.

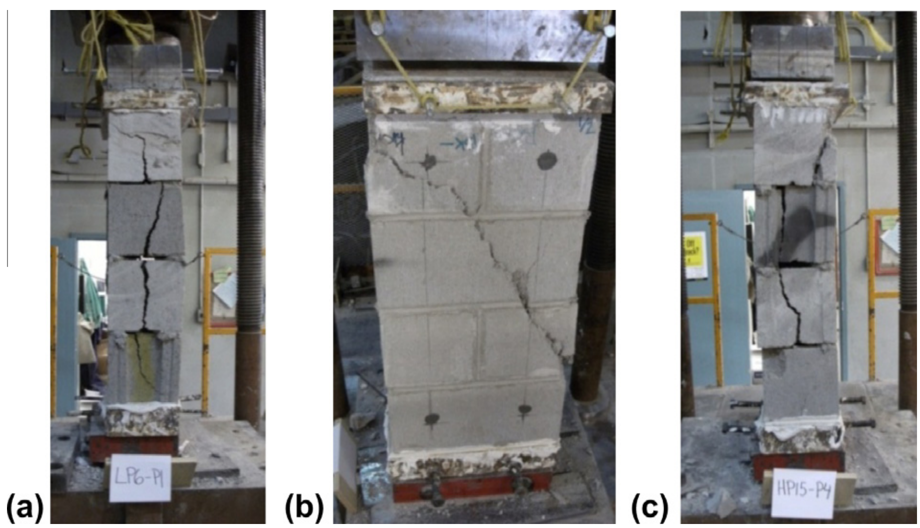

Fig. 9. Failure of prism (a) typical, (b) and (c) for 15% LDPE and 15% HDPE prisms.

the poor bonding between cement paste and polymer pellets [11]. The presence of cracks in the blocks with high percentages of PE also contributed to the increase in water absorption.

The IRA measurements for the blocks, given in Table 6, show the same trend observed for the water absorption. Accordingly, the same argument presented for the water absorption can be extended to explain the IRA results.

3.2.2. Block mechanical properties

The 4-day and 160-day compressive strength of the blocks containing PE aggregate is shown in Fig. 3. The 4-day strength of the 3% LDPE and 3% HDPE blocks is statistically the same as the control; however, for the other block types the strength is lower. With the exception of the 9% LDPE, 15% LDPE and 15% HDPE blocks, the blocks containing PE met the plant production requirement of 12 MPa for the 4-day compressive strength.

All the blocks containing PE aggregate yielded a 160-day compressive strength that was lower than that of the control blocks. The decrease in strength is proportional to the quantity of sand replaced. Moreover, the effect of PE type on the block strength is not statistically significant. When compared to the control, the 160-day compressive strength of the blocks containing 3%, 6%, 9% and 15% LDPE decreased by 20%, 52%, 56% and 70%, respectively. The reductions in the block strength are attributed to the increased porosity of the blocks and the very low strength of the PE aggregate. Moreover, the hydrophobic nature of PE and poor adhesion of PE aggregate with the cement paste contribute to the observed reductions in strength [11]. Similar results were reported in other studies [6,8].

The elastic modulus for each of the block types is shown in Fig. 4. The modulus of the 3% LDPE blocks is statistically the same as the control blocks, but all the other blocks with PE had lower values than the control. Ghaly and Gill [6] reported similar findings, where the addition of plastic aggregate resulted in a decrease in stiffness.

3.2.3. Prism mechanical properties

The compressive strength of the prisms is given in Fig. 5 along with the corresponding mortar strength. Those constructed with blocks containing 3% LDPE, 3% HDPE, or 3% grafted HDPE yielded statistically the same strength as the ones built using the control block. The strength of the prisms constructed with blocks containing 6% and 9% LDPE and 6% and 9% HDPE is statistically greater than 15 MPa and thus can be used for some load-bearing applications. The prisms constructed with blocks containing 15% LDPE or 15% HDPE have a compressive strength lower than 10 MPa.

Although the mortar strength was much greater than that of the blocks strength for the blocks containing high percentages of PE aggregates, it had little effect on the prism compressive strength.

The typical prism failure mechanism is splitting through the webs as shown in Fig. 9a. However, for the prisms made with blocks containing 15% LDPE or HDPE, the mechanism of failure was different. The initial cracks were through the web but then propagated through the face shell of the prism as shown in Fig. 9b and c. This mechanism was also observed for some of the prisms made with 9% LDPE or 9% HDPE blocks. The cause is most likely the weak planes that were formed between the polymer aggregates and the paste that allowed for easy propagation of cracks through the face shell.

The prisms' modulus of elasticity is shown in Fig. 6. The trend is similar to the one presented for the compressive strength. No statistically significant difference was observed between the control's modulus and that of the 3% LDPE, 3% HDPE and 3% grafted prisms. The modulus of prisms built with blocks containing 9% PE is in the range of 15 GPa and can be considered adequate to resist structural load.

The variances in the bond wrench results shown in Fig. 7 are above the limit set by the standard. This is due to the limited number of joints tested and the nature of the bond wrench test. Statistically, the results reveal no difference between the bond strengths of the control and that of the 3% LDPE, 9% LDPE, and 15% HDPE prisms. Moreover, the bond strength of the 6% LDPE, 6% HDPE, 9% HDPE and 3% grafted prisms is greater than that of the control. Only the prism constructed with 3% HDPE blocks yielded lower bond strength than that of the control. A review of the results indicates no correlation between the bond strength and IRA values. Arguments have been made that an increase in IRA can result in an increase in the bond strength and that a substantial increase in a block's IRA could result a decrease in the bond strength due to the increase in the amount of water absorbed by the blocks thereby drying out the mortar before a good bond can be achieved [32].

3.2.4. General discussion

The properties of the blocks are significantly affected by the addition of polymer aggregates beyond 3% sand replacement. The compressive strength and elastic modulus of the blocks and prism followed a linear trend, where an increase in the polymer aggregate content results in a decrease in the mechanical property. The density of the blocks also decreases linearly with the addition of polymer aggregate. The water absorption properties, however, linearly increase with an increase in the polymer aggregate content, with the exception of the 15% HDPE blocks. The 15% HDPE blocks have a higher absorption than would follow a linear trend, but this is likely due to significant cracking in the webs of the blocks observed during block production. There is a very good correlation between the density of the blocks and the compressive strength and elastic modulus of the blocks, that is, the higher the block density, the higher the compressive strength and elastic modulus.

In most cases, there is no statistically significant difference between the results for the mechanical properties for the blocks made with LDPE and those made with HDPE at the same replacement level. The only significant difference is in water absorption when 9% or 15% of the sand is replaced be the two polymer types, with the absorption of the blocks with HDPE being higher than the absorption of the LDPE blocks. From the results, there is no clear benefit to using one type of PE pellet over the other.

Grafted HDPE was used in an attempt to improve the bond between PE and the cement paste, however, there was only enough of the material available to replace 3% of the sand for one batch of blocks. From the results presented, there is no indication that the grafting was beneficial to the blocks. In all case, the blocks with 3% grafted HDPE performed statistically the same or worse than the blocks with the same amount of sand replaced with LDPE or HDPE. So it may be concluded that there is no justification to using grafting to improve the performance of concrete blocks with low levels of PE aggregate, since the hydrophobic nature of the polymer aggregate does not significantly affect the blocks at this level. However, it may become beneficial at higher PE addition levels, where bonding problems were observed during block production, which significantly affects the performance of the blocks and limits their use.

4. Conclusions

From the experimental program, the following effects on the concrete blocks due to the partial replacement of cement, by weight, with WGP were observed:

1. WGP can be incorporated into the production of dry-cast concrete blocks at an industrial plant to produce a useful product with minimal effect on the production process and properties of the final product.
2. The water absorption and IRA tested showed only a minor increase with the addition of WGP.
3. The early strength requirement of the blocks was attained even with 25% cement replacement. Although, the strength development of the blocks with 10% WGP was slower than the control, statistically they achieved the same compressive strength as the control within one-year. The blocks with 25% WGP had a 16% lower compressive strength than the control, after one-year.
4. The use of blocks containing WGP did not have a significant impact on the performance of the prisms tested.
5. No ASR was detected even with 25% of the cement replaced with WGP. WGP maximum particle size was finer than 36 μm.

Based on the observed results, the following conclusions can be made about replacing a portion of sand, by volume, with polymer aggregate:

1. Replacing sand by 3% and 6% polymer aggregate had no negative effect on the production of dry-cast concrete blocks at an industrial plant. However, higher PE addition results in cracking of the block webs due to the hydrophobic nature of the polymers.
2. The density of the blocks decreased with the replacement of sand with polymer aggregate, even at low sand replacements. However, the blocks do not qualify as lightweight.
3. The water absorption and IRA of the blocks increased significantly with the addition of polymer aggregate.
4. Except for the 9% LDPE, 15% LDPE and 15% HDPE blocks, all the blocks with polymer aggregate achieved the required 4-day compressive strength.
5. Addition of polymer aggregates adversely affected the strength of the blocks and prisms. At 3% polymer aggregate content, the block strength decreased between 20% and 25%, depending on the polymer type.
6. The high content of polymer aggregates led to the formation of weak planes that resulted in the development of a failure mechanism that is different from the one typically observed for prisms built using the control blocks or blocks with low polymer aggregate content.
7. The HDPE and LDPE blocks performed similarly and there was no indication that the use of one of these two should be preferred over the other.
8. The quantity of grafted HDPE used was too low to observe any benefits of its use since the hydrophobic nature of the polymers did not become a problem until more than 6% of the sand is replaced with PE.

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