Research Article

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Design and characterization of concrete masonry parts and structural concrete using repurposed plastics as aggregate

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Abstract: Historically known for being one of the major pollutants in the world, the construction industry, always in constant advancement and development, is currently evolving towards more environmentally friendly technologies and methods. Scientists and engineers seek to develop and implement green alternatives to conventional construction materials. One of these alternatives is to introduce an abundant, hard to recycle, material that could serve as a partial aggregate replacement in masonry bricks or even in a more conventional concrete mixture. The present work studied the use of 3 different types of repurposed plastics with different constitutions and particle size distribution. Accordingly, several brick and concrete mix designs were developed to determine the practicality of using these plastics as partial aggregate replacements. After establishing proper working material ratios for each brick and concrete mix, compression tests as well as tensile tests for the concrete mixes helped determine the structural capacity of both applications. Presented results proved that structural strength can indeed be reached in a masonry unit, using up to a 43% in volume of plastic. Furthermore, a workable structural strength for concrete can be achieved at fourteen days of curing, using up to a 50% aggregate replacement. A straightforward cost assessment for brick production was produced as well as various empirical observations and recommendations concerning the feasibility of each repurposed plastic type examined.

Keywords: concrete, masonry, recycled plastics, sustainability, aggregate replacement

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1 Introduction

The overuse of plastic (PL) products in the past years has caused large waste accumulation, which is currently an increasing environmental concern. From the viewpoint of recyclability, PL material can be categorized as recyclable, reusable, and/or disposable [1]. Usually, the disposable-only type is known to have a long degradation time. Accumulation of these PLs brings forth challenges as well as opportunities that will be addressed in this manuscript. The research and data presented herein are the product of a collaboration between the University of Puerto Rico Mayagüez Campus' Nanotechnology Center for Biomedical, Environmental and Sustainability Applications, and a recycling company, (Reciclaje del Norte Ltd., RDN). The company indicated that the types of PLs provided could not be reused and could only be shredded and discarded onto landfills.

PLs are ubiquitous materials with appealing properties. PL products can be found in the automotive, aeronautical, pharmaceutical industries, and many others. However, this material generates post-consumer waste that leads to serious environmental pollution. These discarded PLs not only affect landfills but also water bodies connected to oceans, causing irreparable damage to marine life and aquatic ecosystems [2]. According to some studies, global consumption of plastics increased from 5 million tons in the 1950s to almost 100 million tons in 2001 [1]. In 2003 the US Environmental Protection Agency revealed that in the United States, 80% of PL used is discarded to landfills, 8% is incinerated, and only 7% is recycled [3].

The construction industry is no stranger to these issues being itself one of the most polluting industries in the world. Cement production alone accounts for a significant part of all the CO₂ released into the atmosphere world-

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wide. Its manufacturing process is responsible for between 5-10% of those CO₂ emissions [4].

In unstable economies, constant infrastructure development can represent a significant challenge when trying to lower project expenditures and reduce environmental impact. Materials scientists and engineers seek to optimize construction time and reduce material consumption. Scholars are also determined to minimize the detrimental effects of concrete production by incorporating recycled materials such as PLs, crushed rubber, and coal incineration byproducts (fly ash), among others [5, 6]. In response to these challenges, the main goal of the present work has been to develop new cement-based composite materials, incorporating different categories of recycled PLs, which are difficult to repurpose.

Although PLs are not commonly used in structures or as an aggregate in structural elements, this research sought the development of ecologically friendly non-structural parts (bricks or blocks). In addition, possible limits to the use of this composite as structural component (based on mechanical strength criteria) were investigated. These products can then become an appealing alternative to mitigate PL accumulation in the environment. The following section reports the results obtained from the fabrication of ecologically friendly bricks (or eco-bricks), *i.e.*, masonry bricks made with recycled PLs, as well as potentially structural concrete mixtures bearing those repurposed PLs as aggregate replacements. In closing, the goals of this research efforts have been to repurpose PL waste into easily reproduced masonry pieces and to study the concrete strength loss when PL is added. Thus, future efforts will aim to produce a mix with -at least- minimal structural strength.

2 Methodology

In order to propose alternative uses of recycled PL-containing concrete, several tests were needed to establish baseline performance parameters. This is due to different types and proportions of starting materials rendering considerably different results.

2.1 Materials

The main PLs studied in this research were collected, shredded, stored, and supplied by RDN. These were originally obtained from the industrial wastes of local companies and were deemed by the recycling company “not fit”

for conventional recycling. A collection contract prevents RDN from reverse engineering the composition and structure of the disposed PL pieces. These were mostly stochastic in both their granulometry and assorted composition (similar but different types of PL mixed together). These included a gravel like black-colored plastic that resembled regularly used coarse aggregate (PL1), a hard plastic used in pallets that varied in size and shape (PL2), and mixture of assorted plastics (mostly from disposed medical devices) (PL3). The other components that comprised the study were Portland cement (PC) type I [7] and sand with 1.95 fineness modulus, as fine aggregate [8].

Table 1 shows the densities of the materials used in this project and Table 2 depicts the preliminary mixture design of the bricks. In these mixtures the PL amount and sand content were varied. Special consideration was given to the PL1 mix due to the similarity of this repurposed plastic to other commonly used aggregates in concrete, *i.e.* a close resemblance to black gravel. This resulted in mixture PL1 having four different mix designs, each with different proportions, identified as C1, C2, C3, and C4. Only two mixture variations (C1 and C2) were studied thoroughly for PL2 and PL3 mixes.

Table 1: Materials Densities

Name	Description	Density (gr/cm ³)
PC	Portland cement	3.180
S	Sand	1.580
PL1	Black gravel-like plastic	0.345
PL2	Pallet type plastic	0.476
PL3	Assorted PL mix	0.324

As for the structural concrete, the same plastics were used, *i.e.*, the ones supplied by RDN. In this case, the other components were:

- Portland cement type I, fly ash (FA) class F (low calcium) [9] with a specific gravity of 2.4
- nanoparticles of silica (nanostructured SiO₂) (nS)
- coarse aggregates (gravel) [10]
- fine aggregates (9.5 mm crush rock and sand combination bearing a fineness modulus of 3.0) [8]

The as-provided nanoparticles were opalescent and odorless amorphous silica dispersed in water with an average size of 80 nm, a specific gravity of 2.0 and a pH of 9.7. A superplasticizer (SP), carboxylate polyether type copolymer [11], commercially designed as a high-range water-reducing admixture (HRWRA) ADVA 575, allowed for a more fluid and, therefore, more manageable mixtures. Ta-

Table 2: Mixture designs for eco-bricks (proportions by weight)

Mixture Name	Portland Cement	Sand	PL	Water (% of Total Material Weight)
PL1-C1	1	2	0.250	9-10%
PL1-C2	1	2	0.125	9-10%
PL1-C3	1	1.5	0.250	9-10%
PL1-C4	1	1	0.250	9-10%
PL2-C1	1	2	0.250	9-10%
PL2-C2	1	2	0.300	9-10%
PL3-C1	1	2	0.250	9-10%
PL3-C2	1	2	0.125	9-10%

Table 3: Contents by volume percent of mixtures designs

Mix Number	% PL	% Gravel	PC	FA	nS
MN1	50	50	50	50	0
MN2	50	50	47	50	3
MN3	50	50	100	0	0
MN4	100	0	50	50	0
MN5	100	0	47	50	3
MN6	100	0	100	0	0

Table 3 shows the contents of the six mixture designs: MN1 – MN6, where MN stands for mixture number. As one can observe, 50 and 100% coarse aggregate were replaced in the different mixtures, while the cementitious material contents (PC, FA, and nS) varied from mix to mix.

2.2 Mixing procedure

To prepare the mix for the bricks, a 5L Globe sp-20 mixer machine operated at 60 and 120 rpm cycling speeds was used. The mixture started by adding the aggregates along with PC and, thereupon, mixing it at 60 rpm for fifteen seconds. Afterwards, water was added into the mixture as the mixing proceeded for 3 minutes at 120 rpm until the mix looked wet. This was placed inside an ECO Brava brick machine (Figure 1), in a sealed chamber where hydraulic pressure reduced porosity, densified the mix, and -hence- consolidated the brick.

Figure 2 shows the cube samples cast using cubic molds in order to conduct a preliminary visual inspection of the consistency and color tones (obtained using small quantities of cement coloring agents) of the initial mix batches. Once the desired consistencies and color tones were reached, the final brick dimensions were 7.62 cm thick, 10.16 cm wide, and 20.32 cm long. The bricks were

Figure 1: Eco Brava™ brick casting machine **Figure 2:** Initial cube mix samples

casted, pulled out of the mold, and examined visually. As an empirical measure of quality, the bricks were to slide off the mold without cracking or breaking. After every mixture was completed, the brick machine was cleaned up to prevent any malfunction of the moving mechanisms and cross-contamination.

To prepare the structural concrete samples a similar yet more thorough and controlled procedure was followed. First, the materials were weighed in accordance with mix design specifications (target proportions). In this case, the total amount of water was divided in three identical parts. The coarse and fine aggregates were manually mixed and

Figure 3: Volume percent of Portland cement, sand, and type of PL in the bricks

then placed in the 5-liter mixer. Two of the three parts of the water were then added to the aggregates, which were then mixed at 120 rpm for fifteen seconds. Next, the PC and FA to were added the aggregates as the mixing continued at 60 rpm for fifteen seconds; at this time the nS was added to improve its distribution in the mixture. Afterwards, the final mixing part lasted 4.5 minutes as the SP and the remaining water were incorporated. Once the mixing process concluded, samples according to the proceedings in [12] were prepared. The formwork removal took place 24 hours after casting. Finally, these samples were cured in limewater for 3, 7, and 14 days [12] prior to the corresponding compressive and split tensile tests.

2.3 Mechanical characterization

The bricks resistance was evaluated via a compression test, as the compressive strength is the most important property for the characterization of these types of bricks. A 3,000 kN Forney universal test machine (following [13]) was fitted with one metallic plate placed on the brick to distribute the applied load evenly. Compression strength was computed as the maximum measured load upon fracture divided by the cross-sectional area of the brick specimen. This compression test was performed in the samples (bricks) at curing ages of 3 and 7 days. The same machine measured the compressive and tensile strengths of the structural concrete samples following [14] and [15] standards.

3 Results and discussion

3.1 Feasibility study of masonry units with PL as a partial fine aggregate replacement

During the preliminary stages of the brick experiments, a 1:3 cement / sand ratio was tested, commonly used in conventional bricks. Qualitatively, the experimentation revealed some lack of cohesion between the PL and the matrix (sand/cement), yielding brittle bricks unable to be handled without falling apart. Therefore, for the next step said ratio was changed to one that would allow better mixture consolidation in the machine and that will eventually yield a better brick: 1:2 cement / sand ratio with only 25% PL. This level of PL complicated attaining an adequate quality of the bricks, except for the PL2-C1 mixture, which had a good compacted aspect and a workable integrity; in this case, the resulting brick was readily demolded. Table 4 presents pertinent observations during the bricks manufacturing.

In view of those preliminary results, it was sought to reduce the PL amount for the mixes containing PL1 and PL3. Figure 3 shows the volume percent of each material in the ensuing brick specimens.

Manufacturing speed being crucial in terms of the viability and practicality of the brick, it was given special consideration to the 3-day curing time. Longer curing times were tested but obtained results rendered a dismissible gain of strength. Figure 4 presents the average compres-

Table 4: Summary of observations during brick fabrication

Mixture Identifications	Observations
PL1-C1	Regular compaction (brittle sample) Brittle composition (some cracks observed)
PL1-C2	Good compaction (sound sample)
PL1-C3	Regular compaction (brittle sample) Brittle composition (cracking)
PL1-C4	Regular compaction (brittle sample) Better integrity (some cracking)
PL2-C1	Excellent compaction sturdy composition
PL2-C2	Excellent compaction and excellent integrity
PL3-C1	Poor compaction (not working)
PL3-C2	Regular compaction (brittle sample)

Figure 4: Compressive strength of the bricks according to the plastic type used

sive strength of each brick type, ranging from 6.9 to 22.3 MPa. Mixture PL3-C1 could not retain its shape after casting; therefore, it did not undergo curing and subsequent structural tests.

Finally, Figure 5 shows the overall aspect of final product (labeled “Eco-Bricks”). These pieces were provided to the partnering Reciclaje del Norte company.

To examine the marketing feasibility of the product, a brief cost analysis ensued. Only material costs were included, as this approach could be a more reproducible strategy for a follow-up research. The cost estimate shown in Table 5 was based on the following unit values of the materials (given in US dollars):

- Sand: 0.04 - 0.06 \$/kg
- Portland cement: 0.11 - 0.17 \$/kg
- PLs: 0.01 - 0.03 \$/kg

Figure 5: Final product of colored ornamental bricks containing recycled PLs

Naturally, PC was the most expensive material controlling the final cost of each mixture. Recycled PLs proved to be less expensive than the other fine aggregate material used in the mix (*i.e.* sand). This factor made PLs a viable aggregate replacement when cost is the most important variable considered. It was deemed important to emphasize that, being a recycled material replacing a natural material (sand), the PL also has an ecological advantage. Thus, the resulting mix could potentially become a more marketable product in an increasingly *greener* construction industry. The implementation of such technology could even help designers and developers obtain higher points in coveted LEED certifications [16], appealing to the sustainability and innovative aspect of the award, thus giving projects added value. However, one must mention that the price of the PLs used on this project varied slightly depending on various factors including type, assortment, availability, and quantity obtained.

3.2 Mechanical strength of concrete bearing PL as a partial coarse aggregate replacement

As mentioned before, in addition to the bricks study, a more conventional concrete was developed. These new mix designs had a more fluid constitution and could attain structural strength (approximately 23 MPa for residential use) [17]. Such product would serve a different spectrum of the construction industry while still retaining its sustainable nature. To this end, PL was used to partly and completely replace the coarse aggregate of concrete mixtures containing nanoparticles, which were introduced to partly compensate for the expected strength loss. To test the mechanical properties of these new mix designs, compression and tensile tests were conducted with the same

Table 5: Volume percent and summary of cost for the Eco-Bricks

Mixture	Proportions (Volume %)			Cost \$			
	PC (%)	Sand (%)	PL (%)	PC	Sand	PL	Total
PL1-C1	14	55	31	0.12	0.05	0.02	0.19
PL1-C2	16	65	19	0.14	0.06	0.02	0.22
PL1-C3	16	48	36	0.13	0.05	0.03	0.21
PL1-C4	19	38	43	0.16	0.04	0.03	0.23
PL2-C1	15	60	25	0.13	0.06	0.03	0.22
PL2-C2	14	57	29	0.12	0.06	0.03	0.21
PL3-C1	13	54	33	0.11	0.05	0.02	0.18
PL3-C2	16	64	20	0.14	0.06	0.01	0.21

Figure 6: Compressive strength for mixes containing 50% and 100% of coarse aggregate replacement by PL at 3, 7, and 14 days of aging **Figure 7:** Splitting tensile strength for mixes containing 50% and 100% of coarse aggregate replacement by PL at 3, 7, and 14 days of aging

equipment indicated in the prior section. Table 3 shows the mix design proportions of the six experimental mixtures, designated as MN1 to MN6.

Figures 6 and 7 show the compression and tension test outcomes. Not surprisingly, a 50% loss of compressive strength occurred when 100% of the coarse aggregate was replaced with PL. In similar mixes with no plastic content [18], an extremely detrimental effect on the concrete's strength was observed. However, results also demonstrate that, by limiting the use of plastic as a replacement for coarse aggregate to 50%, the strength nears the structural resistance goal. Figure 3 helps understand better these correlations by comparing MN3 (50% PL replacement) and MN6 (100% PL replacement). MN3 approximately doubles the compressive strength of MN6, suggesting an inverse relation between plastic content and concrete strength. Nonetheless, it was acknowledged that further tests and statistical analyses are required to fully validate this claim given the stochastic nature of concrete failure [19].

4 Conclusions

- In the present work, results suggest that the load bearing capacity of both the masonry units and the experimental concrete was heavily influenced not only by the type of plastic used as aggregate, but also by the proportions used in the mix design, especially plastic and Portland cement. Naturally, these two materials proved to have opposite effects, as higher PC concentrations yielded stronger bricks and experimental concrete mix designs, while higher PL contents lowered such capabilities.
- The bricks containing the “gravel-like” PL had the best integrity and thus the best handling capacity of the PLs used in this study. These bricks displayed a good compact integrity, making the demolding process quick and successful. Through testing trial and error, it was determined that using up to a 43% by volume of PL the brick maintained a good composition (no cracks) while also reaching structural strength.
- The “pallet type” plastic showed an unstable interaction between the aggregate and the cement matrix, which hindered the structural integrity of the brick after removal from the machine, making it prone to crumbling during the demolding phase. For this PL a weight ratio of 1:2:0.125 (PC:sand:PL) was found to be the best. In addition, workable bricks and acceptable compressive strength results were obtained us-

ing 25% and 29% of plastic by volume. Still, it was found that bricks using this type of PL should limit its content to not higher than 19-20% by volume of the brick, to obtain better results.

- Similarly, in bricks containing the assorted plastic mix, the cohesiveness between the plastic and the cement matrix remained an issue. The expansion, attributed to the elastic recovery of the “rubber type” pieces included in the plastic mix, resulted in multiple cracks during demolding. A weight ratio of 1:2:0.125 led to optimum results when working with this specific type of repurposed plastics. Thus, when working with mixed “rubber-like” pieces, to make the final product more manageable, it is recommended that the plastic content percent be under 20% of the brick's volume.
- Most importantly, compressive strength results ranging from 17.3 to 22.3 MPa were obtained. These values exceeded the 17.2 MPa minimum for the structural concrete solid bricks established by [20].

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