Comparing the Properties of Polyethylene Terephthalate (PET) Plastic Bricks to Conventional Concrete Masonry Units

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***Abstract*—This paper investigates the viability of recycled polyethylene terephthalate (PET) bricks as a replacement for concrete masonry units as a building material. The underlying goal is to validate the pursuit of production and testing of recycled PET bricks. Recycled plastic bricks have the potential to divert valuable post-consumer plastic waste from landfills, locking up this plastic for decades to come. A comparison of the material properties, as well as the greater societal impacts, of virgin PET and concrete comprise this study. The compressive strengths of the two materials are compared using both published data and a computational analysis. The toxic substances released during production and post-production of concrete and PET are examined, to gain a deeper understanding of the overall impact these materials have on human health.**

Keywords—polyethylene terephthalate, concrete masonry units, plastic bricks, health hazards, carbon dioxide emissions

I. Introduction

The ever-increasing volume of solid plastic waste produced globally has created a need for purposeful products that lock up this plastic for the long-term. As of 2015, it was estimated that 6300 billion kg of plastic waste had been produced to date, with 79% entering landfills and the environment [1]. Recycling this waste plastic to use as a raw material, and upcycling it into a profitable product, could reduce the quantity of plastics entering land and aquatic ecosystems.

In 2017, plastics were estimated to compose 13.2% of municipal solid waste generation in the United States [2]. Plastics are generally sorted into seven different categories, identified by a corresponding code number [3]. Polyethylene terephthalate (PET) is identified by the code number 1 and is commonly used to manufacture beverage bottles and fibers [3]. Code number 2 identifies high-density polyethylene (HDPE) which is commonly used to make soap bottles and milk containers [3]. The overall plastics recycling rate in the U.S. in 2017 was estimated to be 8.4%, while the recycling rates for PET and HDPE were 29.1% and 31.2 %, respectively [2]. Other common types of plastics, polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), and others constitute the remaining five categories [3]. These varieties of plastic are not recycled as commonly as PET and HDPE.

When designing products to be manufactured from recycled plastic, product longevity and volume of raw material consumed are the most important considerations. To effectively address the plastic waste crisis, products made from recycled plastic need to divert a large quantity from landfills by consuming a considerable amount of raw material, but they also need to maximize the lifespan of the product to keep the plastic in use for as long as possible. Building materials molded from recycled plastic, specifically bricks, met both of these criteria.

With bricks designated as a potential end-product, it was then necessary to choose an appropriate plastic to make these bricks. PET and HDPE were identified as top contenders because they are readily available in the waste stream and commonly recycled. In addition to its availability in the waste stream, PET also has a greater compressive strength than other common polymers [4]. Creep, a time dependent strain resulting from a continuous stress, is a common mode of failures for plastics. Given that PET is more creep-resistant than HDPE, it was chosen as the target material for brick manufacturing [5].

Using recycled PET to manufacture plastic bricks is advantageous given the product longevity of bricks, which will keep plastic locked up for longer than many other applications, such as packaging. Many institutions have conducted research on recycled plastic-concrete composites, which replace a portion of the aggregate material with recycled plastic. While plastic concretes offer promising potential, they are typically weaker than conventional concretes due to the poor bonding between the cement and the plastic. This paper addresses the potential for bricks made entirely from plastic, which eliminate the structural shortcomings of plastic-concrete composites. The existence of companies already manufacturing plastic bricks suggests that they are a viable alternative; however, little published research on the topic exists. This paper addresses this knowledge gap.

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Developing a meaningful application for recycled PET will encourage recycling, reducing the volume of plastics currently reaching a final destination in landfills or waterways and minimizing the economic costs associated with plastic pollution. Additionally, shifting production of bricks from concrete to recycled PET could aid in reducing global greenhouse gas emissions. Producing cement, one of the key components of concrete, is one of the biggest contributors of carbon dioxide, a known greenhouse gas. It is estimated that 5-8% of anthropogenic sources of CO_2 emissions can be attributed to the production of cement [6, 7]. Relying on recycled plastic instead of cement as a raw material could drastically reduce the environmental impact of brick manufacturing.

This article presents a comparison of PET and concrete in building applications. The article begins with a focus on material properties, specifically mechanical and thermal properties, with support from a finite element analysis. The societal impact of both materials is addressed, with regard to environmental impact and associated human health hazards. The lack of published data for the use of recycled PET in structural applications manifests a need for future experimental research.

II. Background Work

The traditional recycling process currently in place is unable to resolve plastic pollution due to economic limitations in the market. Large-scale recycling is becoming less profitable, and the degree of contamination tolerated by these facilities is getting lower, forcing more valuable post-consumer plastics into landfills. These post-consumer plastics, usually considered to be waste, can act as an inexpensive raw material in innovative applications. As society is becoming more aware of the plastic crisis, innovators are using their creativity to seek alternative solutions to reuse plastics, particularly in the construction industry.

In academia, researchers have started to explore the concept of incorporating recycled plastic into concrete as either aggregate or fiber. By 2016, over 80 research studies had been conducted on both plastic aggregates (PA) and plastic fibers (PF) concretes [8]. Aggregates make up 60 to 75% of concrete and play an influential role in concrete's material properties [9]. In the case of PA concretes, the natural aggregate content is substituted with plastic aggregates at specific concentrations [8]. Researchers have noted that the compressive strength, elastic modulus, splitting tensile strength, and flexural strength of PA concrete decreases as increasing amounts of PA are substituted for natural aggregate in the concrete [8]. However, an MIT study in 2017 found that PA concrete can become up to 15% stronger than conventional concrete if the plastic is pre-exposed to small doses of gamma radiation, then pulverized into fine powders before mixing the plastic with cement paste and fly ash [10]. Unlike PA concretes, PF concretes contain strands of plastic that act as reinforcement for the concrete. Studies have shown that PF concrete with a composition of less than 1% plastic has higher compressive, splitting tensile, and flexural strengths compared to conventional concrete [8].

Outside of academia, there is a growing market for building materials made from recycled plastics. A plethora of organizations, from industries to social enterprises, are striving to design products and processes with the twin goals of combating the plastic crisis and operating a profitable business. Some of these organizations have chosen to manufacture products out of recycled plastics such as bricks, panels, thermal walls, and thermal roofing. One such Philippines-based company is Green Antz that is producing Eco-bricks from a mix of cement and plastics [11]. Each Eco-brick contains 100 sachets [11], which are non-recyclable plastic laminates. Eco-bricks are molded in shapes that closely resemble Lego bricks in order to withstand an appropriate compressive load and connect to neighboring pieces. Each brick has a compressive strength of 3792 kPa, which is significantly greater than the hollow concrete block (1089 kPa) that is currently being used in the Philippines [11]. In addition to their superior compressive strength, Eco-bricks have an average price of PHP 830 per square meter, beating its hollow block competitor of PHP 900-1100 per square meter [11].

In addition to producing building materials made of recycled plastics at the unit level, some companies take the commitment to the systems level where they assemble their plastic products into larger-scale products. An example of a company that is creating products out of recycled plastics at the systems level is EcoDom. Based in Mexico, EcoDom is combating the plastic crisis and poverty by using recycled plastics to create thermal walls, concrete roofing, thermal roofing, and structural beams to build affordable homes for low-income communities [12]. In taking advantage of plastic's insulation properties, EcoDom homes have a high thermal insulation system. The company's easy to assemble products allow each home to be assembled in seven days [12]. While providing affordable housing for a family, each home also diverts two tons of plastic from the landfill [12].

This paper investigates the viability of using PET as a replacement for conventional concrete masonry units in building applications. Specifically, it introduces the possibility of producing bricks composed entirely of PET, relying on data for pure PET with the intention of further testing to understand the properties of recycled PET.

III. Materials and Methods

This paper aims to address the viability of PET as a substitution for concrete as a building material. Specifically, the structural integrity of PET from a material properties standpoint was investigated and compared to concrete. The greater societal impact of manufacturing both materials was also investigated so as to understand the effects on human health and the environment. The data within this paper was primarily compiled from existing studies. To maintain consistency and rely upon the most readily-available data, this study compares pure PET and concrete. It is important to acknowledge that material properties may vary slightly between recycled and pure PET, as well as between variations of concrete that use different aggregates. Additional experimental research regarding the properties of recycled PET will be presented in a future paper.

The finite element analysis was conducted following the ASTM Standard C90-16a minimum required load of 12.4 MPa [13]. A model for a block of dimensions 20.32 cm × 20.32 cm × 40.64 cm (8 in × 8 in × 16 in) was generated in SolidWorks and was imported into Ansys Workbench. The load was applied to the top face with the bottom face statically secured. The study analyzed the maximum principal stresses that occur in the geometry and those maximum stresses were compared against the materials' known compressive strength.

IV. Results and Discussion

A. Mechanical and Thermal Properties

The comparison of PET and concrete in building applications began with an analysis of several material properties. Compressive strength is one of the most important properties to consider. The ASTM standard that details the Standard Specification for Loadbearing Concrete Masonry Units (C90-16a) also recognizes density and water absorption as important properties [13]. Additionally, two thermal properties, linear coefficient of thermal expansion and thermal conductivity, were investigated.

The compressive strength of the two materials is of critical importance because in the context of a wall, each brick must bear a portion of the compressive load of the other bricks, as well as the load associated with the roof. ASTM standard C90-16a, requires that individual units have a minimum compressive strength of 12.4 MPa [13]. Published values for the compressive strength of PET vary. A data sheet for unreinforced PET lists the compressive strength as 45.2 MPa, which was the minimum value encountered when consulting various sources [14]. Another source lists the compressive strength of PET at 80 MPa [4]. Even at the minimum value, PET meets the compressive strength requirement for concrete masonry units. The density of PET is 1.35 g/cm^3, which is less than that of concrete at 2.4 g/cm^3 [15]. The lower density would reduce the associated compressive load on other bricks. Additionally, a PET brick of the same size as a traditional concrete block will weigh less, decreasing the work required to lift and assemble the blocks for a wall. Low density blocks are also preferred in earthquake-prone regions [16]. ASTM standard C90-16a specifies that the maximum water absorption for concrete must range from 240 - 320 kg/m^3, depending on the density [13]. The average value for PET is measured as a percentage, with an average value of 0.304% [4]. Water absorption is used to predict the durability of concrete because water facilitates the penetration of the material by aggressive substances [17]. The presence of water in concrete can also induce cracking due to thermal expansion and contraction with temperature changes. However, the porosity of PET is much lower, minimizing concerns about water absorption.

When considering materials for building applications, it is also important to analyze their thermal properties. PET has a linear coefficient of thermal expansion (CTE) of 117 × 10^{-6} °C^{-1}, and concrete has a CTE value of 10.0 × 10^{-6} to 13.6 x 10^{-6} °C^{-1} [15]. In climates with fluctuating temperatures, the CTE value indicates the degree to which the material will expand or contract with changes in temperature. PET has a significantly higher CTE value than concrete, which could result in regions of stress if the bricks are in contact with a material that has a lower CTE. This could also pose a problem in regions which experience a freeze-thaw cycle [18]. The thermal conductivity is also important to consider, as it quantifies the ability of a material to act as an insulator. PET has a thermal conductivity of 0.15 Wm^{-1}K^{-1} compared to concrete whose thermal conductivity value is 1.25 - 1.75 Wm^{-1}K^{-1} [15]. Lower thermal conductivity corresponds to enhanced insulation capability, so the lower value for PET indicates that less heat will be conducted by the material. This will reduce heating and cooling costs in a structure built primarily from PET bricks. These findings suggest that PET would serve as an appropriate substitute for concrete, as it has comparable or superior material properties important for building.

B. Finite Element Analysis

A finite element analysis (FEA) was conducted on a standard concrete masonry unit (CMU) geometry using both the material properties of concrete and of PET. As discussed previously, the ASTM standard C90-16a specifies the minimum pressure a CMU must withstand to be 12.4 MPa [13]. The study found the maximum principal stresses that occur in the brick, and these principal stresses were compared against the maximum compressive strength and the maximum compressive yield strength for concrete and PET respectively. A brief table of the results is included below.

TABLE I. RESULTS OF FINITE ELEMENT ANALYSIS

Material	Maximum Compressive Strength (MPa)	Maximum Principal Compressive Stress (MPa)
Concrete	18	7.11
PET	45.2	21.9

As expected, the block made of concrete passed the ASTM minimum strength requirement. The block of PET passed as well and would therefore be a feasible material to replace concrete for a building block material. Screenshots of the FEA are included below in Figs. 1 and 2.

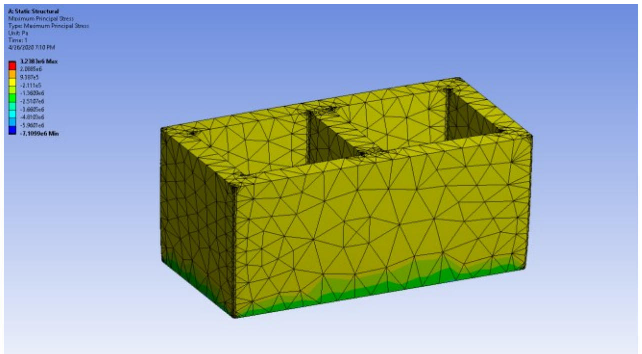

Fig. 1. Results of finite element analysis of compressive load applied to a standard concrete masonry unit. The minimum principle stress, which corresponds to the maximum compressive stress, was 7.11 MPa.

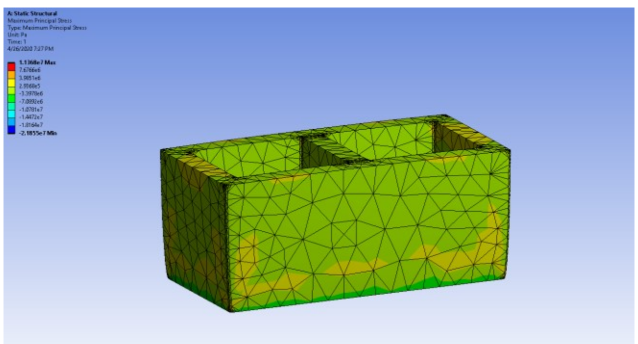

Fig. 2. Results of finite element analysis of compressive load applied to a PET block with the dimensions of a standard concrete masonry unit. The minimum principle stress, which corresponds to the maximum compressive stress, was 21.9 MPa.

The study above was conducted using the material property data for virgin PET only, as there is no sufficient research on the compressive yield strength of a recycled PET material. It is worth noting that the results may vary when using a recycled PET brick, as the mechanical properties may degrade from the virgin material.

C. Health Hazards

When comparing these two materials, it is also important to consider the risks that their production pose to human health. According to the Occupational Safety and Health Administration (OSHA), job-related injuries and illnesses for concrete manufacturing workers are common, with approximately 10% experiencing these complications over a one-year period [19]. Exposure to cement dust causes frequent eye, skin, and respiratory irritation, and wet concrete can allow alkaline compounds to chemically burn skin [19]. Silica exposure can lead to significant lung injuries including silicosis, bronchitis, and lung cancer [19]. A study has found that subjects chronically exposed to cement dust also have a greater risk of getting cancer of the lung and larynx [20]. Not only this, but frequent inhalation of cement particles can affect gastrointestinal, lymphatic, and central nervous systems negatively as well, causing complications like dental abrasion, diminished lymphatic tissue, and headaches [20]. To preserve the health of future cement manufacturers and construction workers, substituting cement for another building material may be most suitable.

OSHA does not classify PET as hazardous, and it has not been found to be carcinogenic [21]. However, PET production still poses health risks. Data from the Environmental Protection Agency shows that several toxic chemicals are released into the air during PET manufacturing, including nickel, ethylbenzene, ethylene oxide, and benzene [22]. PET is stable in ambient conditions but can produce toxic vapors during thermal decomposition at high temperatures [21]. As a result, hazardous explosions, chemical fires, chemical spills, and clouds of toxic vapor have stemmed from the plastic production [22]. Large-scale PET recycling is becoming increasingly important as the production of virgin PET jeopardizes human health. One of these recycling efforts could potentially be directed at the use of recycled PET as a building material.

The main health concern associated with PET as a building material involves its potential to emit volatile organic compounds (VOCs). VOCs are gases that include a variety of chemicals that can cause eye, nose, and throat irritation, shortness of breath, headaches, fatigue, nausea, dizziness, and skin problems [23]. In a recent study on the effect of artificial weathering on plastic, it was concluded that PET is highly stable and resistant to photo-oxidation due to the presence of structural aromatic rings, which reduced the amount of volatile organic compounds released during aging when exposed to environmental conditions over a one-month duration [24]. In this study, PET only released 10 µg/g of VOC emissions, which is remarkably low when compared with other types of plastics that experienced simulated weathering; LDPE released 1,500 µg/g, HDPE released 500 µg/g, PP released 1,500 µg/g, and PS released 1,700 µg/g [24]. This shows that under environmental weathering, insignificant amounts of VOCs will be released from PET over time. In an additional study of PET granules, acetaldehyde and formaldehyde (common VOCs) were shown to be emitted, but at a temperature of 200–300°C [23]. These extremely high temperatures have never been recorded in weather history, further illustrating PET's potential as a safe building material.

D. Greenhouse Gas Emissions

A comparison of CO_2 emissions associated with production of concrete and PET is important for understanding the greater societal impact of these materials. Concrete is a widely known source of CO_2, mainly because of the production of cement, a key ingredient in concrete. A 2013 estimate reported that 5-7% of anthropogenic sources of CO_2 emissions stems from the production of cement, whereas a 2018 estimate reported that the number was close to 8% [6, 7]. In Europe, cement plants run on 90% fossil fuels, but another source of CO_2 causes an even bigger problem [7]. More than 50% of the CO_2 released in the production process of cement stems from the production of clinker, the major component of cement [7]. Cement is manufactured by inputting ground limestone and clay into a rotating kiln at >1400°C [25]. The calcination of the limestone produces CO_2 and clinker [6, 25]. The EPA reports that in 2001, the estimated national weighted average carbon intensity for cement production was 0.97 ton of CO_2 per ton of cement produced [26], and a 2013 article estimates that the number is 0.66 to 0.82 kg CO_2 for every kilogram of cement manufactured [6]. In addition to the release of CO_2, there are also combustion-relation emissions from the production of cement that include methane and nitrous oxide. 3.7% of combustion related emissions from the US industrial sector come from the cement industry [26]. Gasses like methane and nitrous oxide are greenhouse gasses even more powerful than CO_2 [26]. When investigating the CO_2 emissions of PET during recycling processes, the following data was found [27]. Approximately 200 kg CO_2 was produced per metric ton of recycled plastic collected. When compared to the 1900 kg CO_2 released during the manufacture of PET, the 200 kg is the obvious choice for reduced emissions. The vast majority of emissions produced during PET recycling are created during the cleaning process, which makes it a clear target for increased efficiencies.

To recycle one kg of plastic, 0.17 kg of CO_2 is released (not including transportation emissions). On the other hand, to produce one kg of cement, 0.66 to 0.82 kg of CO_2 is produced. Since cement makes up approximately 15% of concrete by weight [28], the contribution of CO_2 emissions for concrete is approximately 0.10 to 0.12 kg CO_2 per kg concrete produced. This estimate does not account for CO_2 emissions caused by transportation cement of the other 85% of concrete by weight [28]. The CO2 emissions stemming from production of concrete and the recycling of PET are comparable. However, this does not take into account the CO2 emitted from transportation of large weights of sand, water, and aggregate that is included in concrete.

V. Conclusions

A comparison of pure PET and concrete from several angles concluded that PET bricks could act as an adequate substitute for conventional concrete masonry units. PET not only offers superior strength and insulation capability but is also safer for the laborers producing the materials and has lower associated greenhouse gas emissions. The motivation of this research was to understand the potential for producing PET bricks as an avenue to reduce plastic waste. Recycled PET will likely behave differently than pure PET and the likelihood of impurities is increased, and hence future work on this pursuit will focus on laboratory testing. Overall, the initial findings indicated that PET bricks will be a superior, safer, and more sustainable alternative to concrete masonry units.

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