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Irradiated recycled plastic as a concrete additive for improved chemo-mechanical properties and lower carbon footprint

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ABSTRACT

Concrete production contributes heavily to greenhouse gas emissions, thus a need exists for the development of durable and sustainable concrete with a lower carbon footprint. This can be achieved when cement is partially replaced with another material, such as waste plastic, though normally with a tradeoff in compressive strength. This study discusses progress toward a high/medium strength concrete with a dense, cementitious matrix that contains an irradiated plastic additive, recovering the compressive strength while displacing concrete with waste materials to reduce greenhouse gas generation. Compressive strength tests showed that the addition of high dose (100 kGy) irradiated plastic in multiple concretes resulted in increased compressive strength as compared to samples containing regular, non-irradiated plastic. This suggests that irradiating plastic at a high dose is a viable potential solution for regaining some of the strength that is lost when plastic is added to cement paste. X-ray Diffraction (XRD), Backscattered Electron Microscopy (BSE), and X-ray microtomography explain the mechanisms for strength retention when using irradiated plastic as a filler for cement paste. By partially replacing Portland cement with a recycled waste plastic, this design may have a potential to contribute to reduced carbon emissions when scaled to the level of mass concrete production.

1. Introduction

The use of recycled plastics in concrete has been explored as a means of improving concrete's mechanical properties while also providing an efficient way to both repurpose waste plastic and partially displace cement for the purpose of reducing carbon emissions. The task remains, however, to develop a cement design that allows for both the addition of plastic and the preservation of high compressive strength. This study explores the effectiveness of gamma-irradiated plastic as an additive in cement paste (Portland cement + additives + water) samples for improving the compressive strength. Irradiated plastic is paired with different mineral additives, which are commonly used to achieve high strength, with the goal of finding an optimal combination. An internal microstructure analysis is presented in order to provide some insight into the aspects of the materials' chemical compositions that contribute to the observed variation in strength. The objective is to determine whether or not irradiated plastic is an effective partial replacement for cement; achieving a high/medium-strength concrete using this additive would imply the ability to produce a lower carbon footprint concrete variety that could even act as a permanent storage option for plastic waste.

1.1. Carbon emissions in the cement industry

Concrete is the second most widely used material on the planet, after water (Crow, 2008). The cement industry accounts for roughly 5% of global anthropogenic carbon dioxide emissions, making it a critical sector for emission mitigation (Worrell et al., 2001). The production of Portland cement releases carbon dioxide both directly and indirectly (Ali et al., 2011; Tanaka and Stigson, 2009). Direct emissions result from a process known as calcination, which occurs when limestone, the primary component of cement, is heated (Andres et al., 1996). The calcium carbonate in the limestone breaks down into calcium oxide and carbon dioxide (Taylor, 1997). This process accounts for roughly half of all emissions from cement production. To produce cement, limestone and other clay-like materials are heated in a kiln at around 1400 °C. Indirect

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emissions result from the burning of fossil fuels to heat the kiln and account for about 40% of cement production emissions. The electricity used to power additional plant machinery, as well as the final transportation of cement, account for the remaining 10% of total emissions. These emissions make partial replacement of cement with a substitute material an attractive alternative to alleviate the negative environmental impact of cement production.

1.2. Plastic waste and recycling

Constituting a separate environmental issue is the abundance of plastic waste. Plastics have come to play an essential role in our everyday lives. Their favorable properties, including low cost, high strength-to-weight ratio, and low density make them ideal for use in a wide range of products (Gu and Ozbakkaloglu, 2016; Singh et al., 2017). It has been shown that over half of global plastic production is used for one-off disposable consumer products. This contributes heavily to the production of plastic-related waste, most of which is not biodegradable and will not react chemically in natural settings, and therefore it remains in the environment for decades or even centuries. Plastic wastes have become universally accepted as a serious environmental issue.

Despite improvements in technology and awareness that have occurred since the recycling of plastic waste began in 1980, the recycling rate of post-consumed plastic wastes is still fairly low (EPA, 2014). A 2012 study showed a plastic recycling rate of only 8.8%, while the remaining 91.2% was simply discarded. The discarded plastic is typically put into a landfill, which is considered the least desirable method of dealing with plastic waste because it demands heavy space consumption and contributes to long-term pollution (EPA, 2014; Gu and Ozbakkaloglu, 2016). In some countries waste plastic is incinerated for energy recovery because of its high calorific value. This method, however, produces toxic ash and releases carbon dioxide and poisonous chemicals into the environment. Recycling, therefore, is seen as the ideal solution for minimizing environmental impact. Among the various approaches to managing recycling are (1) standard mechanical recycling, which aims to recover plastic via mechanical processes (sorting, grinding, cleaning, drying, re-granulating, etc.) and produces recyclates that can be transformed into new plastic products, and (2) recycling in the form of repurposing the waste plastic without fully breaking it down (Al-Salem et al., 2009). Mechanical recycling degrades the quality of the plastic during the service cycle, and often times the plastic that is recycled in the United States is exported, with about two-thirds being shipped to China (Gu and Ozbakkaloglu, 2016). This is due to the fact that the U.S. recycling market is small in comparison to other countries (Yoshida, 2005). The exported plastic is shipped overseas via massive cargo ships, which collectively release billions of tons of CO_2 annually, along with considerable amounts of nitrogen and sulfur (Corbett and Fischbeck, 1997). Thus reusing waste plastic in in other industries is considered a more ideal method of disposal (Gu and Ozbakkaloglu, 2016).

1.3. Plastic as an additive in concrete

The use of a wide range of plastics as additives to concrete, in the form of powder, aggregate and fiber, has been extensively studied by several researchers (Asokan et al., 2010; Choi et al., 2009; Gesoglu et al., 2017; Kim et al., 2010; Siddique et al., 2008). Recently, researchers have explored waste and recycled plastic's potential as an environmentally friendly construction material by repurposing it as an additive in concrete mix and studying the concrete's resultant behavior (Gu and Ozbakkaloglu, 2016). Specifically, polyethylene terephthalate (PET) has been explored as a lightweight concrete aggregate that could improve various mechanical properties and replace the standard lightweight aggregates that are typically used, which face some problems related to both cost and quality (Choi et al., 2005). A recent study shows that manufactured plastic aggregate can be used at 25% replacement level for natural aggregates while providing a benefit of light weight aggregate concrete subsequently maintaining the required strength and ductility for non-structural applications (Alqahtani et al., 2017). Another work demonstrates that plastic from bottles shredded into small PET particulates was successfully used as sand-substitution aggregates in cementitious concrete composites (Marzouk et al., 2007). Moreover, use of plastic aggregates from foam-extrusion process has led to improved aggregate/binder interface, and reduction in dead-weight of the structure and overall reduction in consumption of natural sand (Coppola et al., 2016). Also, inclusion of plastic as an aggregate can lead to significant reduction in the thermal conductivity subsequently improving the thermal insulation performance of the mortars (Colangelo et al., 2016; Iucolano et al., 2013). Plastic aggregates have five times lower thermal conductivity than silica based aggregated which can be used to control the heat loss from buildings during summer and heat gain in the winter. For detailed review on usage of waste plastic as an aggregate in mortar and concretes the readers are referred to a state of art review article by Saikia and de Brito (2012).

PET is a polymer notable for being the constituent of the clear plastic used for soda and water bottle containers. In comparison to Polypropylene (PP) and polyethylene (PE), PET in concrete can improve the concrete's flexural toughness, impact resistance, and workability (Choi et al., 2005; Kim et al., 2010; Pelisser et al., 2012). Moreover, PET is highly sensitive to the alkaline environment in the pore solution of cementitious matrix, which can act as a precursor that can contribute to dense forming phases. Various studies have shown mixed results for improvements in tensile strength (Saikia and Brito, 2013). Compressive strength, however, has generally been shown to decrease with the addition of PET. Thus it is apparent that the task remains to produce a PET-enhanced concrete capable of demonstrating the aforementioned mechanical improvements without compromising its compressive strength.

1.4. Gamma irradiation of PET

One potential solution for recovering some of the strength back that is lost when plastic is added to concrete is to make use of irradiation to improve the concrete's strength properties (Martínez-Barrera et al., 2006, 2011, 2005). PET is a semi-crystalline polyester that exhibits an isotropic microstructure due to its glassy amorphous composition (Jog, 1995). For this reason, it is one of the most studied polymers. Upon irradiation, the two effects of greatest importance for PET are chain scission and crosslinking (Plester, 1973). It has been shown that, due to the chain scission effect, the degree of crystallinity in PET increases with gamma radiation dose (Kattan, 2006). The number of chain scissions increases with dose, thereby decreasing the molecular weight. This reduced weight accounts for improved molecular mobility, which facilitates the ordered arrangement of molecules in crystalline structures. Thus the increase in mobility as a result of chain scission leads to greater crystallizability when PET is irradiated by gamma rays. The extent of crystallinity has a significant impact on several mechanical properties of PET (Demirel et al., 2016). Higher crystallinity PET has been shown to have higher modulus, toughness, stiffness, strength, and hardness. Alternatively, crosslinking is the chemical bonding of one polymer chain to another (Plester, 1973). It can be induced by radiation and has the effect of strengthening the chemical structure of the compound. Thus both chain

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