Effect of differently shaped recycled PET plastic on the early-age properties of cement mortar

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Abstract
The purpose of the study was to obtain detailed information about the early-age properties of mortars with differently shaped recycled PET plastic particles as partial natural aggregate replacement. The properties of mortar mixtures were investigated using commonly applied techniques upgraded by X-ray diffraction (XRD). Results showed that shape and surface roughness of PET particles significantly affect the properties of cement mortars by improving flowability of fresh mixtures, decreased flexural strength, and increased compressive strength. XRD also confirmed fewer hydration products due to the presence of PET particles in the mortar.

Keywords
Cement mortar, early-age properties, natural aggregate, PET plastic waste, recycling

Introduction

In the last fifty years, production of plastics has been steadily increasing. Global plastics production in 2020 reached 367 million tonnes, while European plastics production itself reached 55 million tonnes which is almost 15% of global production. The European plastics demand in 2020 was 49.1 million tonnes, mostly from the packaging industry (40.5%), construction and building, and the automotive industry [1]. One of the most commonly used plastics in the packaging industry is polyethylene terephthalate (PET) which is mostly used for the production of bottles or smaller containers [2]. PET plastic products are known to be easily available and affordable. However, the negative side of increasing PET plastic production is the large amount of PET plastic waste that causes environmental issues. Most PET plastic products are made for single use only which is one of the main reasons that this type of plastic quickly becomes waste [3, 4]. PET plastic has relatively high collective and recycling rates [5, 6]. Also, different technologies in the recycling processes of PET plastic are playing the most important role to prevent contamination of new products when PET plastic is being reused for various purposes [7, 8].

Several past studies have reported that the use of recycled plastic waste contributes to the reduction of natural aggregate consumption in the construction business, with the possibility of improvement of concrete properties while at the same time, it reduces the amount of plastic waste to be managed [9]. It was found that the compressive, tensile, and flexural strength of mortar samples increased when 5–10% of the natural fine aggregates were replaced by PET particles from ground bottles. It was also indicated that replacement higher than 10% resulted in a significant decrease in strength-related parameters of the samples [10]. However, Saikia and de Brito [11] found that regardless of the type of PET-aggregate and curing time, the strengths and modulus of elasticity of the concrete containing PET-aggregate were lower than those of the reference concrete. It was confirmed that the content of PET in the composite is crucial.

The most important reasons for recycled PET plastic application in building materials are a shortage of natural aggregates in some parts of the world and PET plastic waste reduction [9, 12]. Interestingly, most of the past studies investigated higher replacement ratios in cementitious composites (> 10%) and focused on the size of PET plastic particles when replacing natural aggregates [9, 13]. None of the studies so far highlighted the importance of the shape of plastic particles.

The purpose of this research was to determine the early-age mechanical properties of cement mortars containing different shapes of recycled PET plastics as partial natural aggregate replacement.

Materials and Methods

Ordinary Portland cement CEM I 42.5 N, the natural aggregate of 0/4 mm, and 3 differently shaped recycled PET plastics (Figure 1) were used for this research. The maximum size of recycled PET plastic particles used in mortars was 4 mm. PET granules and PET particles ground like a sand was equally recycled from waste translucent PET bottles but differently moulded after extrusion. PET flakes were recycled (mechanical recycling) from waste black PET boxes. Each shape of recycled PET plastic was used as a partial natural aggregate replacement in a mortar (5% of the volume of natural aggregate). The water to cement ratio (w/c) of 0.45 and cement content of 450 kg m^{-3} of cement mortar was used for all mortar samples. Composition of mortar mixtures are presented in Table 1.

The fresh density of cement mortars was determined conforming to SIST EN 1015-6:1998 and the flowability of fresh mortar mixes was determined according to SIST EN 1015-3:2001.

The compressive and flexural strength of prism samples (40 × 40 × 160 mm) were tested 3, 7, and 28 days after moulding. Both strength tests were conforming to SIST EN 1015-11:2020.

A PANalytical X'Pert PRO diffractometer was used for X-ray diffraction (XRD) analysis to determine the crystallographic structure of cement mortars.

Table 1. Composition of cement mortars.

Component	Content (kg m^{-3} of cement mortar)			
	Plain mortar (control)	PETG	PETS	PETF
Cement	450	450	450	450
Water	209.19	208.86	208.86	208.86
Sand	1673.62	1589.94	1589.94	1589.94
PET plastic	/	43.14	41	37.9
Superplasticizer (by weight of cement in plain mortar)	9.45	9.45	9.45	9.45

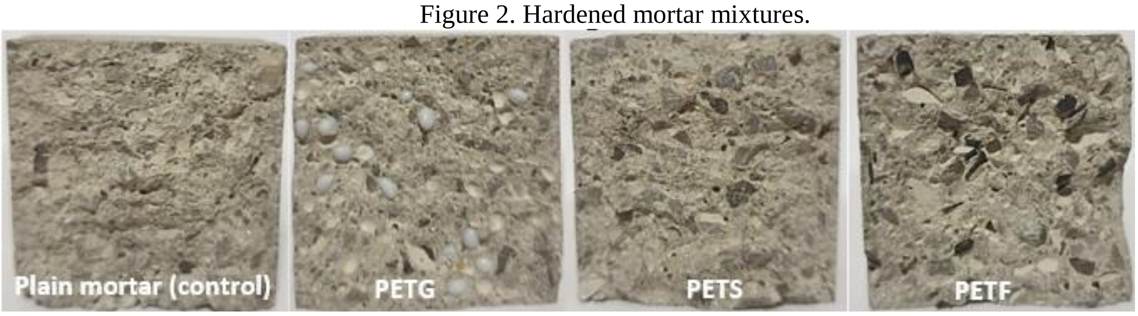
Notes: PETG=mortar with PET granules; PETS=mortar with PET particles ground like sand; PETF=mortar with PET flakes.

Figure 1. Different shapes of recycled PET plastic used in cement mortars.

Results and Discussion

A comparison of PET-containing mortars and the control mortar confirmed that each shape of recycled PET plastic differently affected the properties of fresh mortar mixtures. Hardened mortars are shown in Figure 2.

Figure 2. Hardened mortar mixtures.



The properties of fresh PET-containing mortar mixtures are presented in Table 2. PET plastic as a partial natural aggregate replacement significantly increased the flow diameter of mortar with PET particles like sand (PETS) and mortar with PET flakes (PETF) while mortar with PET granules (PETG) had similar flowability as plain mortar. Overall, the flowability of mortars improved due to PET content in mortar mixtures. The fresh density of mortars containing PET plastic was lower compared to the control mix. However, on average, the differences are very small compared to plain mortar.

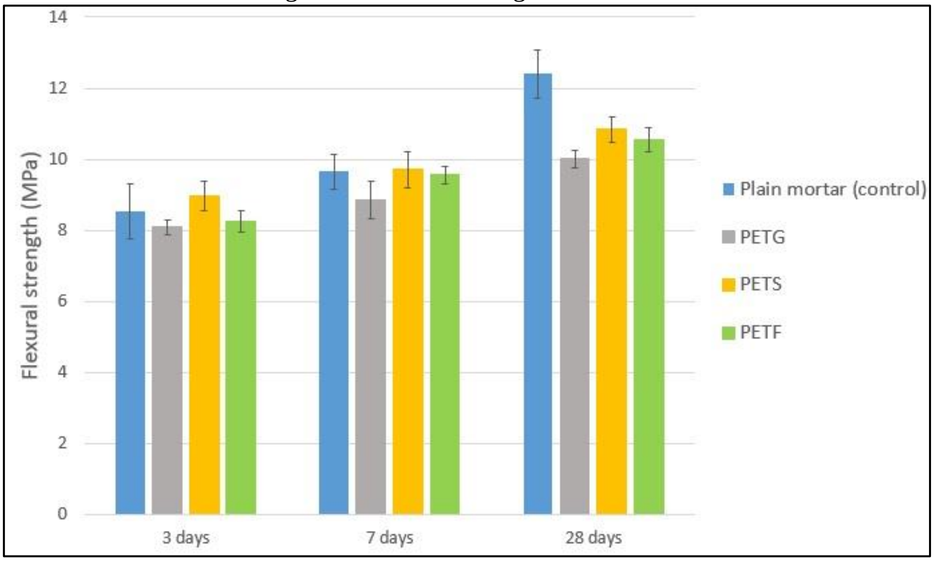
Table 2. Flowability and fresh density of fresh mortar mixtures.

	Mortar mix			
	Plain mortar	PETG	PETS	PETF
Flow diameter (mm)	127±2.5	127±0.7	171.3±5.3	168.3±2.4
Fresh density (kg m^{-3})	2342.10±0.30	2285.15±0.95	2336.20±1.40	2308.80±1.00

Notes: PETG=mortar with PET granules; PETS=mortar with PET particles ground like sand; PETF=mortar with PET flakes.

Strength tests revealed that the shape of PET plastic significantly affects flexural and compressive strength. PETG mortar mix showed a decrease in 3-day, 7-day, and 28-day flexural strength compared to plain mortar as a control mortar mix (Figure 3, Figure 4). A significant decrease was found in 28-day flexural strength which was approximately 20% lower than the control (Figure 3). PETS and PETF mortars had 3-day and 7-day flexural strengths similar to plain mortar while 28-day strengths were significantly lower than the control. Interestingly, Abed et al. [14] reported in the study an increase in the 28-day flexural strength of mortar with 5% of PET pellets which increased about 16%, while increasing the content of PET in mortars significantly decreased the flexural strength of mortars. Ismail and Al-Hashmi [15] also confirmed a decrease of the flexural strength of concrete due to PET content.

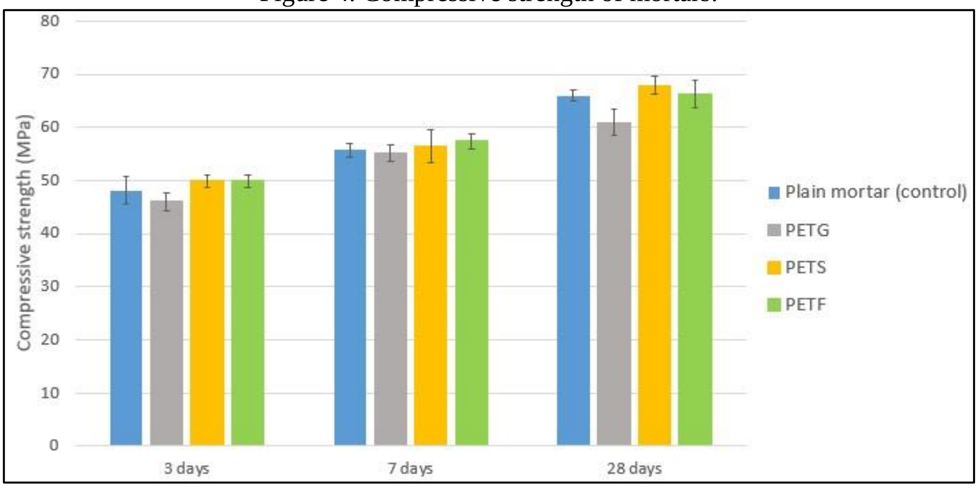
Figure 3. Flexural strength of mortars.



The results of the compressive strength test are shown in Figure 4. The comparison of plain mortar and PET-containing mortars revealed PETG mortar had lower strengths than the control. On the contrary, PETS mortars showed slight increase at 3- and 7-day compressive strength compared to plain mortar. However, the increases in strength were only up to 5% higher than the compressive strength of plain mortar. A similar study with different shapes and sizes of recycled PET plastic was conducted by Saikia and de Brito [11]. The results showed that all shapes of PET plastic significantly deteriorated the properties of hardened concrete [11]. However, Rahmani et al. [16] found the 5-day strength of concrete containing 5% of PET plastic as sand replacement showed a slight increase compared to the control with no PET. Frigione (2010) [17] confirmed that compressive strength slightly decreased when PET plastic was added to the concrete as a substitution for natural sand.

Ismail and Al-Hasmi [15] suggested the decrease in strength can be attributed to the decrease in adhesive strength between the surface of the PET plastic and the cement paste. That confirmed the results of this study for PETG mortar which contained PET granules with smooth surfaces and showed a significant decrease in strength compared to other mortars with PET particles with a rougher surface. Also, plastic is a hydrophobic material and can restrict the water which is necessary for cement hydration from entering through the structure of cement mortars during the curing period of mortars.

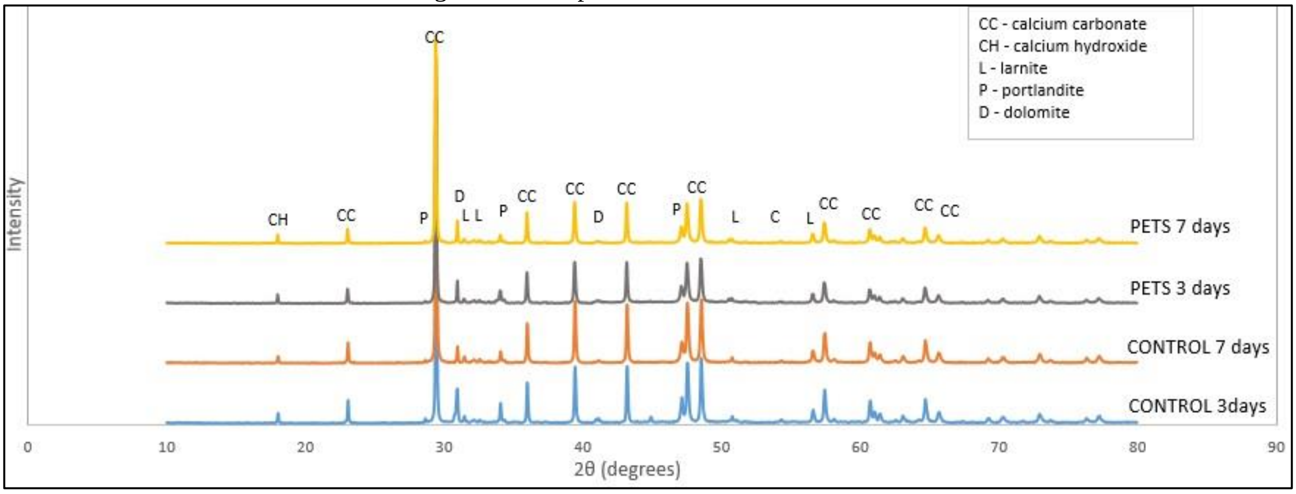
Figure 4. Compressive strength of mortars.



The XRD was conducted to identify the crystallographic structure of a cement mortar due to the addition of recycled PET plastic as a partial natural aggregate replacement. Results of strength tests showed PETS mortar had the most significant increase in 3-day and 7-day flexural and compressive strength. According to these results, XRD analysis was used to compare and provide details about the crystallographic structure of the control and PETS mortar. The XRD patterns of selected mortars are presented in Figure 5.

Five main crystalline phases were detected in mortar samples: calcium carbonate (CC), calcium hydroxide (CH), portlandite (P), larnite (L), and dolomite (D). It was found the intensity of peaks was in PET-containing mortars lower than in the control mortar. The main reason was a smaller amount of natural aggregate in mortar because of the partial replacement with recycled PET plastic and at the same time fewer hydration products due to the presence of PET particles in mixtures. Also, the intensity peaks of PET were not detected due to the amorphous structure of PET.

Figure 5. XRD patterns of mortar mixtures.



Conclusions

In conclusion, the shape and size of recycled PET plastic have a significant influence when replacing natural aggregate on both fresh and hardened cement mortar properties. Results indicated PET flakes and PET particles ground like sand present an appropriate natural aggregate replacement according to the mechanical properties of plain cement mortar. The main reason is the shape and roughness of PET particles' surface. PETS mortar containing PET particles ground like sand indicates the importance of the similarity of PET particles to natural aggregate. However, further research is needed to determine the other properties of such cementitious composites in more detail.

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References

[1] Plastics – the facts 2021 – Plastics Europe, Plasticseurope.org. Available on-line at: https://plasticseurope.org/knowledge-hub/plastics-the-facts-2021/

[2] Nisticò, R. (2020). Polyethylene terephthalate (PET) in the packaging industry. *Polymer Testing*, *90*, 106707.

[3] Alabi, O. A., Ologbonjaye, K. I., Awosolu, O., & Alalade, O. E. (2019). Public and environmental health effects of plastic wastes disposal: a review. *J Toxicol Risk Assess*, *5*(021), 1-13.

[4] Thachnatharen, N., Shahabuddin, S., & Sridewi, N. (2021, March). The waste management of polyethylene terephthalate (PET) plastic waste: A review. In *IOP Conference Series: Materials Science and Engineering* (Vol. 1127, No. 1, p. 012002). IOP Publishing.

[5] Ajaj, R., Abu Jadayil, W., Anver, H., & Aqil, E. (2022). A Revision for the Different Reuses of Polyethylene Terephthalate (PET) Water Bottles. *Sustainability*, *14*(8), 4583.

[6] Ügdüler, S., Van Geem, K. M., Denolf, R., Roosen, M., Mys, N., Ragaert, K., & De Meester, S. (2020). Towards closed-loop recycling of multilayer and coloured PET plastic waste by alkaline hydrolysis. *Green chemistry*, *22*(16), 5376-5394.

[7] Ragaert, K., Delva, L., & Van Geem, K. (2017). Mechanical and chemical recycling of solid plastic waste. *Waste management*, *69*, 24-58.

[8] Eriksen, M. K., Pivnenko, K., Olsson, M. E., & Astrup, T. F. (2018). Contamination in plastic recycling: Influence of metals on the quality of reprocessed plastic. *Waste management*, *79*, 595-606.
[9] Mercante, I., Alejandrino, C., Ojeda, J. P., Chini, J., Maroto, C., & Fajardo, N. (2018). Mortar and concrete composites with recycled plastic: A review. *Science and Technology of Materials*, *30*, 69-79.
[10] Azhdarpour, A. M., Nikoudel, M. R., & Taheri, M. (2016). The effect of using polyethylene terephthalate particles on physical and strength-related properties of concrete; a laboratory evaluation. *Construction and Building Materials*, *109*, 55-62.
[11] Saikia, N., & De Brito, J. (2014). Mechanical properties and abrasion behaviour of concrete containing shredded PET bottle waste as a partial substitution of natural aggregate. *Construction and building materials*, *52*, 236-244.
[12] Ioannidou, D., Meylan, G., Sonnemann, G., & Habert, G. (2017). Is gravel becoming scarce? Evaluating the local criticality of construction aggregates. *Resources, Conservation and Recycling*, *126*, 25-33. https://doi.org/10.1016/j.resconrec.2017.07.016.
[13] Siddique, R., Khatib, J., & Kaur, I. (2008). Use of recycled plastic in concrete: A review. *Waste management*, *28*(10), 1835-1852.
[14] Abed, J. M., Khaleel, B. A., Aldabagh, I. S., & Sor, N. H. (2021, August). The effect of recycled plastic waste polyethylene terephthalate (PET) on characteristics of cement mortar. In *Journal of Physics: Conference Series* (Vol. 1973, No. 1, p. 012121). IOP Publishing.
[15] Ismail, Z. Z., & Al-Hashmi, E. A. (2008). Use of waste plastic in concrete mixture as aggregate replacement. *Waste management*, *28*(11), 2041-2047.
[16] Rahmani, E., Dehestani, M., Beygi, M. H. A., Allahyari, H., & Nikbin, I. M. (2013). On the mechanical properties of concrete containing waste PET particles. *Construction and Building Materials*, *47*, 1302-1308.
[17] Frigione, M. (2010). Recycling of PET bottles as fine aggregate in concrete. *Waste management*, *30*(6), 1101-1106.