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Experimental Characterization of Mortar with Recycled PET Aggregate: Preliminary Results

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Abstract

Plastic materials have been widely used since 1930s-1940s and, at the beginning, their capacity of low degradation was neglected, resulting in negative effect today. The main disposed methods of high volume of plastic wastes are landfill, recycling or composting and combustion. The conflicts between the high costs and relatively low effectiveness make landfill not ideal for the degradation; at the same time, air pollution and the by-products of combustion still need to be resolved with regards to combustion. Therefore, a sustainable and eco-friendly method of handling plastic waste is an immediate requirement.

In literature, was found that one feasible application is to use plastic waste in construction material such as concrete and mortar, thus playing the role of the aggregate in the mix-design.

Therefore, the main object of this paper is to study the influence of polyethylene terephthalate (PET) in the mortar, considering workability and mechanical properties (in terms of flexural and compressive strength). During the experimental work, fine sand was substituted by same volume, namely 0, 5 and 10 % of PET in mortar and all the specimens were subjected to the mechanical tests at the curing time of 7 days and 28 days.

The results showed that as the level of replacement increased, the flexural strength and compressive strength decreased, although with 10% PET the flexural strength showed a slightly increase. Flexural toughness factors were also evaluated and the experimental results showed that with increasing substitution level, the flexural toughness factor showed a slight increase.

Keywords: Mortar; lightweight mortar; recycled PET aggregate; mechanical properties; flexural fracture energy

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1. Introduction

Plastic materials have been widely application in the consumer field since mass production in 1930s-1940s. However, the lower capacity of degradation was neglected at the beginning resulting in negative effect on the human and wildlife and great threat to planet nowadays. Annually 300 million metric tonnes of plastic waste were been produced and a large amount of them nearly 3% were deposited into marine environment (Cressey, 2016).

The main disposed methods of high volume of plastic wastes are landfill, recycling or composting and combustion. Before 1980s, recycling and combustion of plastic was negligible; 100 percent was therefore discarded. From 1980 combustion came to use, and 1990 recycling started to be paid attention although the rates increased on average by about 0.7% per year. It is predicated by Geyer et al. (2017) that by 2050, combustion rates would increase to 50 percent; recycling to 44 percent; and discarded waste would fall to 6 percent in which the concrete or mortar projections are not represented.

However, the conflicts between the high costs and relatively low effectiveness make landfill not ideal for the degradation, and land-space consumption is also a constraint for landfill (Awoyera and Adesina, 2020). Air pollution and the by-products of combustion need to be solved. Therefore, a sustainable and Eco-friendly method to manage the plastic waste is immediate requirement. In addition, reuse and recycling of plastic wastes have been found to be more effective when compared with landfill and incineration (Lazarevic et al., 2010).

Polymers exist organically or can be created synthetically and consist of chains of joined individual molecules or monomers. The difference between polymers and plastics is that plastics are a type of polymer composed of chains of polymers which can be partially organic or fully synthetic. Thermoplastics encompass a wide range of materials including: polyethylene (PE), polystyrene (PS), polypropylene (PP), polyvinyl chloride (PVC), polyester, nylon, acrylonitrile butadiene styrene (ABS) and polyethylene terephthalate (PET), although PVC is not belong to the family of thermoplastics, but it is also world-wide used.

Different plastic showed different physical and mechanical properties:

(1) PE can be further classified by density into high density polyethylene (HDPE), low density polyethylene (LDPE) and linear low-density polyethylene (LLDPE), the density range of HDPE is 0.94-0.97 g/cm^3, for LDPE is 0.91-0.94 g/cm^3, and LDPE has the properties of high impact strength at low temperature and excellent resistance to acids, bases and vegetable oils and is flexible and good transparency, while HDPE has the properties of excellent chemical resistance and high tensile strength;

(2) The density of PP is 0.9-0.91 g/cm^3, it has good resistance to environmental stress cracking but is sensitive to microbial attacks, like bacteria;

(3) The density of PS is 1.01-1.04 g/cm^3, but a white foam plastic material produced from solid beads of PP named Expanded Polystyrene (EPS) may be more well known, EPS showed very low thermal conductivity and exceptional dimensional stability and is not hygroscopic;

(4) the density of PVC is 1.16-1.58 g/cm^3, PVC is considered as a lightweight, durable, good insulation, self-extinguishing and abrasion-resistant material;

(5) density of PET is 1.37-1.45 g/cm^3, PET is known for the properties of high strength and stiffness, excellent electrical insulating, transparent, which is suitable for mineral water and carbonated soft drinks, rigid cosmetic jars, microwavable containers, transparent film but it is easy to be corroded by alkalis and strong bases.

Notable actions have been taken to reduce the production of plastic and increase the recycle of plastic waste. One application is to use plastic waste in the construction material such as concrete and mortar work as the aggregate in the mixture similar to other recycled aggregate concrete (Xiong et al., 2021). There are already pioneering researches on the application, and some review papers have focused on the related researches, Saikia and De Brito (2012) discussed preparation and curing of the cement mortar and properties of the fresh and hard concrete and mortar, Mercante et al. (2018) discussed the positive and negative effects of plastic aggregate on concrete and mortar. Almeshal et al. (2020) also made a critical review on plastic aggregate as fine aggregate in concrete and mortar, and part of physical properties, mechanical properties and durability are also illustrated. However, Saikia and De Brito (2012), Mercante et al. (2018) and Almeshal et al. (2020) reviewed the properties of mortar and concrete together, and more attention was paid to concrete, which means some special properties like thermal conductivity, durability performance of mortar are insufficient, and the influence of curing time is also disregarded.

The object of this paper is to report a preliminary investigation about the effect of the partial substitution of sand with PET by volume on the physical and mechanical properties of mortars, and the relationship between these properties and the substitution level. The preliminary experimental findings of the present work will be integrated with the effect of other percentage substitution level, curing time and curing conditions in a forthcoming study.

2. Materials and methods

The materials used in this study is tap water, Ordinary Portland cement of 52.5R, standard sand, superplasticizer with a density of 1100 kg/m^3 and recycled PET powder, density of 1370 kg/m^3. The particle size distributions of standard sand and recycled PET powder are showed in the Fig.1.

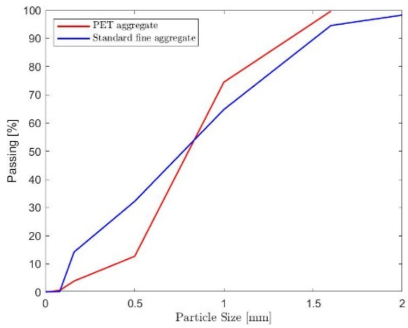


Fig.1. Particle size distribution of sand and recycled PET aggregates

The mix design of mortar was divided into five groups with and without PET aggregates, as showed in Table 1, fine aggregate was systemically substituted with PET aggregates at 0, 5, 10 and 20 % by volume. The mortar specimens were prepared using dry PET aggregate to avoid an increase of porosity due to the presence of free water released from plastic aggregate Coppola et al. (2018), water to cement ratio was controlled at 0.42, fine aggregate to cement ratio was 3, super-plasticizer to cement ratio (by weight) was 1%.

Table 1. Mix proportion of mortar.

Type	*r*	Water	Cement	Water-cement ratio	Sand	Superplasticizer	Recycled PET aggregate
[-]	[%]	[g]	[g]	[-]	[g]	[g]	[g]
NAM	0				1350		0
PETM5	5	189	450	0.42	1282.5	4.5	35.66
PETM10	10				1215		71.31

NAM: Reference Mortar

PETMX: Mortar with X% substitution of PET aggregate

Mix order and the time controlling can be depicted as following: first, super-plasticizer was added into water, and the solution and cement were mixed for 30s under low speed; then, mixing the PET aggregate and fine aggregate together, they were added and mixed for another 30s; next the mixer was turned to high speed for 30s; later, the paste was kept still for 90s; finally, the paste was mixed for another 60s with high speed. In the end, the mortar paste was poured into steel mould in two steps and compacted 60 times each, according to UNI 196-1 (2016).
Three 40×40×160 mm^3 prisms were cast for each mortar mixture. 24 hours after casting, specimens were demoulded and stored in the water under $20\pm1\ ^{\circ}C$. For each cast, mini-slump test (cylinder of 8 cm diameter and 8 cm height) was performed, according to JGJ/T 341 (2014), as already done in the relevant literature, Yuanliang et al. (2021), in order to assess the effect of partial substitution level of sand with PET on the workability of the fresh cementitious paste. In addition, as the substitution level of sand with PET affects the mortar density, the latter was also assessed.
Hardened properties - density, flexural and compressive strength, fracture energy, as explained in Falliano et al, (2019) - were evaluated after 7 days and 28 days of curing. In particular, in Fig.2 is illustrated the apparatus used for three-point bending test in CMOD mode; after the collapse of the notched beam, the compressive test was performed on the

two halves of the broken prism.

Fig.2. The apparatus for flexural tests

3. Result and discussion

3.1. Workability

Table 2 showed the results of the slump; the latter is significantly influenced by the volume of PET aggregate, indeed higher *r* induced lower slump, which is related to the greater water absorption capacity of PET powder than fine aggregate: in turn the water in cement matrix is reduced and the consistency of fresh mortar increases. Bulk density in fresh state is in a good agreement with other papers, Kaur and Pavia (2020). However, contrary results can be found by other investigations (Safi et al., 2013; Hannawi and Prince-Agbodjan, 2015; Rubio-de Hita et al., 2018). Safi et al. (2013) used PET waste with particle size of 1-5mm and an evidently increasing of slump with higher substitution level of PET waste aggregate, (Hannawi and Prince-Agbodjan, 2015) substituted fine aggregate in the mortar matrix by PC granules with maximum diameter of 5mm and this also induced an increase in slump. Same increase also can be found in the study of Rubio-de Hita et al. (2018) with PC flakes. Difference in slump can be explained by the effects of plastic aggregate size; PET powder in this study generates higher specific surface area (SSA) than plastic aggregate in Safi et al. (2013), Hannawi and Prince-Agbodjan, (2015) and Rubio-de Hita et al. (2018), which induced higher water absorption capacity and in turn decrease the slump (Celik, 2009).

Table 2. Properties of fresh state.

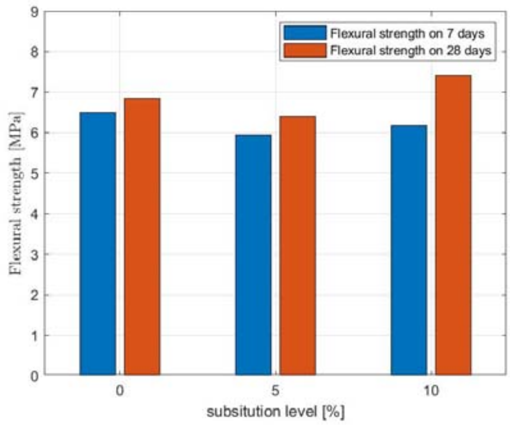
r [%]	0	5	10
Slump [mm]	23	15	12
Fresh density [kg/m^3]	2332.03	2230.47	2209.64

With increasing *r*, the density is decreasing which is related to the lighter density of PET aggregate compared to that of sand. The fresh density loss ratios are 4% and 5%respectively when *r* varies from 5% to 10%. The same fresh density loss ratio range can be found in the research of (Hannawi et al., 2010; da Silva et al., 2014; Kaur and Pavia, 2020). In particular, in this study, the substitution by PET powder induces moderate reduction on the fresh density compared to other size and type of plastic aggregate, such as Rubio-de Hita et al. (2018).

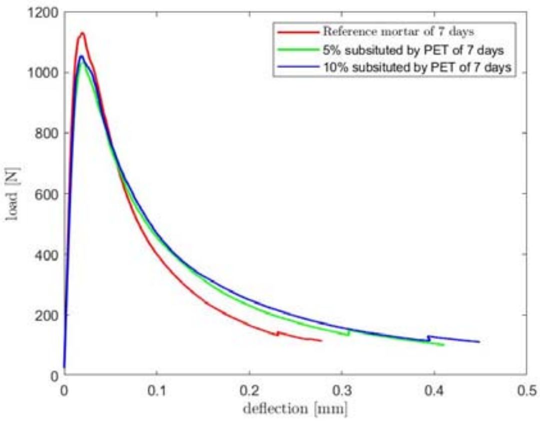
3.2. Flexural behavior

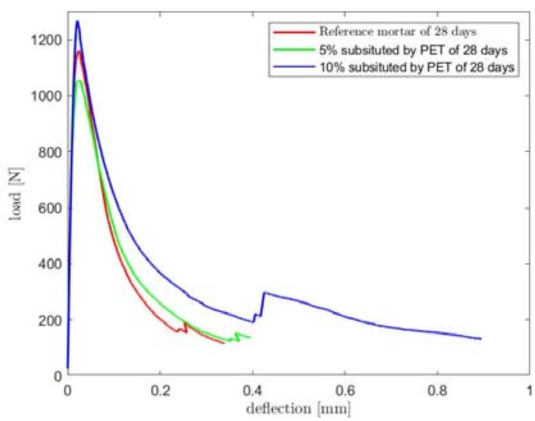
In this study, flexural load-deflection and corresponding flexural properties were investigated for each mixture. A notch with length of 40mm, width of 5mm and depth of 12mm was made by the cutting machine in the middle of specimen one typical notched specimen was showed in the Fig.2. The flexural tests were conducted on a notched specimens according to JCI (2003) with Zwick-Roell servo hydraulic closed-loop test machine under displacement control at the rate of 0.03mm/min. Two LVDT sensors were sticked on the middle of notched surface symmetrically, the deflection of neutral axis was measured by the LVDT sensors, the apparatus was showed in the Fig.2. Load and deflection are constantly recorded during flexural tests.

The quasi-static flexural tests were carried out on 7 days and 28 days of notched specimens. The results of flexural strength are reported in the Fig.3. Generally, the average flexural strength not always decreases with increasing the *r* of PET aggregate. For 7 days, when r=5% there is a slight reduction on flexural strength, while a small increase can be observed in r=10% than r=5%. Regarding 28 days, the tendency is similar with flexural strength of 7 days, but a large increase in r=10%can be observed; the increase ratio is near 10% than reference mortar. Similar results can be obtained in Hannawi et al. (2010); Ohemeng & Ekolu (2019); Badache et al. (2018); Kaur & Pavia (2020).



(a)





(b) (c)

Fig.3. (a) Flexural strength; (b) Flexural load-CMOD curves on 7 days; (c) Flexural load-CMOD curves on 28 days

The flexural load-deflection results of the different *r* are depicted in the Fig.3. Overall, the results indicates that the load-deflection relationships of PET-substituted fine aggregate mortar are characterized by the same typical behaviour. After an initial linear portion lasting up to about 50-70% of the peak flexural load, the curve becomes non-linear. With increasing of r, the flexural deflection at break point increase, which is supposed to the contribution of PET aggregate. Higher substitution levels of PET aggregate augment the capability of resisting the tensile stress and in turn improve the ductility of mortar. The flexural load-deflection curves can be explained by the ability of recycled plastic aggregates to prolong crack propagation interval (Hannawi et al., 2010).

3.3. Compressive strength

Fig.3. showed the results of the compressive strength of mortars with varied *r*. Compared with reference mortar, the compressive strength decreases with increasing r. In particular, when r=10%, the strength reduction ratio is near 25% for 7 days cured specimens, while the strength reduction ratio is more than 15% for 28 days. The negative effect of PET aggregate on compressive strength is caused by the low adhesion effect between the PET aggregate and cement paste (Badache et al., 2018).

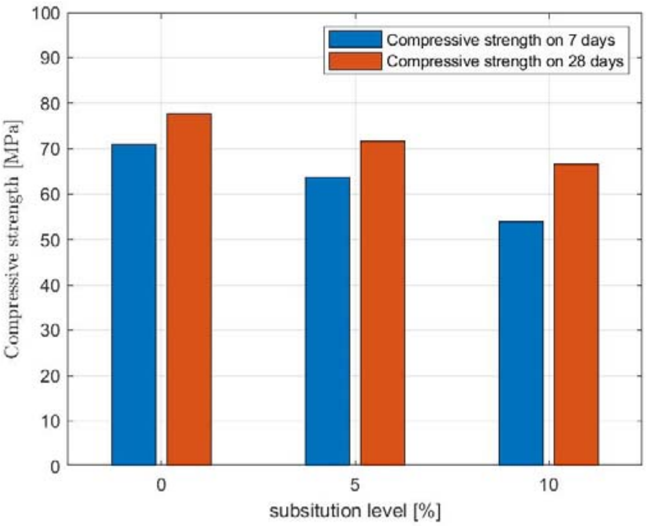


Fig.4. Compressive strength on 7 days and 28 days

3.4. Fracture energy

The fracture energy G_F of the mortar can be derived as follows (JCI, 2003):

$$G_F = \frac{0.75W_0 + W_1}{A_{\text{lig}}} \quad (1)$$

$$W_1 = 0.75(\frac{S}{L}\text{m}_1 + 2\,\text{m}_2)\bullet \text{g} \bullet \text{CMOD}_r \quad (2)$$

Where W_0 is the area below load-deflection (also called as CMOD: crack mouth opening displacement) curve up to failure (J/m^2); m_1 is the mass of specimen; m_2 is the mass of loading jig; S is the length of load span, in this study

is 120mm; L is the length of specimen, nominal length is 160mm; $CMOD_r$ is the crack mouth opening displacement at the time of rupture; A_{lig} is the area of broken ligament.
Average values of fracture energy are presented in the Table 3.

Table 3. The fracture energy.

Type [-]	Fracture energy of 7 days [N/m]	Fracture energy of 28 days [N/m]
NAM	80	90
PETM5	100	110
PETM10	110	170

PET powder significantly improved flexural fracture energy probably since the bridging action between fine aggregate and cement in post-cracking stage and enhanced energy dissipation capacity. Therefore, as found in the relevant literature for other strategies such as biochar addition, Falliano et al (2020), Restuccia et al (2016), replacing sand with waste PET can be a useful way to improve the fracture energy of cementitious based materials as well. Regarding the fracture energy on 7 days, a slight increase can be observed. While a notable increase can be seen when r=10% for 28 days. Higher substitution level and longer curing times lead to greater fracture energy absorption.

4. Conclusion

Based on the results of this study, the substitution of sand with recycled PET powder decreases the compressive strength. Regarding the flexural behaviors, the average strength does not always decrease with increasing the substitution level of PET aggregate: at 28 days determinations, there is a modest reduction compared to the reference value when r=5%, while an interesting increase is observed when r=10%, due to the contribution of PET powder on the capability of resisting the tensile stress. In addition, the fracture energy is always increasing, especially for higher substitution levels.

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