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Concrete-Polymer Composites in Circular Economy

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Innovative Building Materials Containing Post-Consumer Plastics: A Rewarding Example of Circular Economy in Construction

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Abstract. Circular Economy, which it is among the priorities of the European Commission, is defined as an economy in which the value of products, materials and resources is maintained for as long as possible and the production of waste is reduced to minimum. Keeping in mind the impact on the environment caused on the one hand by post-consumer plastic waste and on the other hand by production processes of concrete, it is possible to find a solution able, at least partly, to mitigate these two issues. Following the principles of the circular economy, in fact, it is possible to reuse post-consumer plastic waste as fine aggregates in concrete: in this way, post-consumer plastic from waste becomes a resource; at the same time, the use of other natural resources is limited, such as the minerals traditionally used as aggregates in concrete. However, this virtuous solution still presents some problems to study and solve: this work aims to illustrate some of these issues, and provides indications on the aspects to be analyzed and solved.

Keywords: Circular economy · Concrete · Post-consumer plastics · Recycling · Sustainable building materials

1 Introduction: Circular Economy Principles

Circular Economy (CE) is defined as an economy in which the value of products, materials and resources is maintained for as long as possible; this can be achieved by reusing, repairing, reconditioning and recycling existing materials, extending their life cycle and minimizing the production of waste. It is among the priorities of the European Commission to support sustainable growth and job creation [1]. The demand for raw materials is, in fact, continuously increasing while the natural resources are going to be depleted, resources that are essential for an economy struggling with a constantly growing world population. Furthermore, the procurement of raw materials (not available internally) leads to dependence on other Countries, and we have recently learned how much this can damage a Country's economy. Actions in this direction give a strong boost to product and process innovation, with an increase in competitiveness and economic growth.

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The adoption of the principles of the CE is also an effective response to current environmental issues, as the processes of extraction and use of raw materials produce a great impact on the environment and increase energy consumption and CO_2 emissions. Furthermore, according to CE waste can become a profitable resource, no longer a problem to be managed: it is possible to generate value from waste. The economic model long pursued thanks to a large availability of materials and energy, which involved an enormous exploitation of resources with massive production of waste, must be replaced by a more sustainable model in which waste must be reused/recycled, thus returning economic value to an asset, at the same time reducing its disposal costs. To this regard, Circular Economy strategies can offer new opportunities also to plastic waste which can be recycled instead of being dumped into the environment causing the well-known serious environmental problems. CE represents, therefore, a model for a closed system which promotes the reuse of plastic products in a logic of conservation of resources, generates value from waste producing new eco-sustainable products, and avoids sending a material that is still recoverable to landfill.

2 Post-Consumer Plastics: Disposal and Recycle

In 2020, the world plastic production reached 367 Mtons while the European plastic production was 55 Mtons [2]. After a significant decline in the first half of 2020 due to the pandemic, the production of plastics has recovered since the second half of the same year. The recovery was conditioned by the impact of the pandemic which increased the demand for plastics by major industries, for the production of disposable personal protective equipment and to cope with the massive demand for packaging for shipping of products during the global lockdown. At the same time, many companies have faced supply chain disruptions, raw materials shortages and rising energy prices.

In 2020, the demand of plastic materials in Europe reached 49.1 Mtons, the packaging and construction sectors representing by far the largest end users of such materials. The polymers mainly used in these industries are polyolefins (i.e. polyethylene, PE, and polypropylene, PP), polystyrene (PS), polyvinyl chloride (PVC) and polyethylene terephthalate (PET). At the end of their useful life (probably very short in packaging applications), these polymers are not completely biodegradable, their biodegradation being extremely slow and occurring to a limited extent only in appropriate environmental conditions. On the other hand, if released in the environment, these plastic materials can represent a serious threat to the environment and ecosystems. Therefore, their recovery would avoid these problems allowing to decrease materials extracted from non-renewable resources. In 2020, more than 29 Mtons of post-consumer plastic waste were collected in Europe [2]. Of these, more than a third was recycled and over 40% was recovered as energy. However, over 23% of collected plastic waste were still sent to landfill.

If from the one hand plastic waste represents a valuable resource that can be employed to produce new polymeric materials to manufacture plastic parts and products, on the other hand the recycle of such materials presents many challenges: it is not always practicable and economically convenient. In fact, post-consumer plastic flows are only partially exploited [3], and when, in most cases, their recycling is not possible, they are burned to generate energy, this solution implying a waste of non-renewable natural resources. Therefore, alternative solutions are needed to fully exploit plastic waste to produce new materials and products.

3 Valorization of Post-Consumer Plastic Waste in Construction Sector: Issues

An example of possible route to recover and valorize the post-consumer plastic waste is represented by their use in construction, and in particular to produce concrete.

Considering that concrete is the most commonly used construction material [4], if post-consumer plastics, for instance packaging and disposable items, were systematically employed on an industrial level as raw materials for the production of concrete, this would benefit the environment in several ways. This use as raw materials could reduce the use of minerals traditionally used as aggregates. Post-consumer plastic, dispersed in small particles can, in fact, satisfactorily replace the fine aggregates, enhancing some of the final properties of concrete. Plastic wastes have less weight per unit volume than concrete aggregates, therefore their use as aggregates will reduce the unit mass of concrete structures. The insulation characteristic of post-consumer plastic-concrete is also going to increase.

Research is very active in this field: different experimental studies describe, for instance, the use of post-consumer PET bottles in concrete [5, 6]. The concretes containing PET particles as aggregate are generally reported to be very resistant in both compression and flexure compared to conventional Portland cement concrete. The tensile strength has been found generally increased due to the bridging action of plastic fibers in concrete. Referring to workability of fresh concrete, some literature reported an increase in workability with the addition of small percentages of waste PET while others reported an opposite influence, probably due to the different shape, size, mechanical properties and origin of the waste plastics. It is generally recognized, however, that if a proper mix design is identified, improvements of mechanical and physical properties can be achieved in PET-modified concrete. Additionally, the waste PET does not require any particular treatment before the addition in concrete, i.e. neither cleaning nor removal of colors.

On the other hand, there are many aspects still to be analyzed and investigated. First of all, the cost of production of the post-consumer plastic-concrete is high, still not competitive to conventional concrete. It is therefore necessary to identify applications in which these new materials can be conveniently used, i.e. where they are competitive on the market also in relation to their performance.

Post-consumer plastic waste typically contains different types of polymeric materials in different percentages and with different shapes. The streams of post-consumer plastics are, in fact, composed of different polymers, largely polyolefins (high density and low density polyethylene, i.e. HDPE and LDPE, respectively, and polypropylene), polystyrene, polyethylene terephthalate (Fig. 1), while the international scientific literature mainly analyzes the use of individual polymers (PET only, PE only, etc.) in concrete [7]. On the other hand, the separation of the different polymers composing post-consumer plastic waste is a quite expensive process, not always easy to implement (different polymers have very similar densities). Therefore, if the separation of different types of polymers would be necessary before their addition into the concrete, this would lead to a further increase in production costs. It is therefore necessary to evaluate if by using different plastic waste as aggregates in concrete, without their prior separation, it is possible to obtain concretes with properties and performances comparable to traditional concretes.

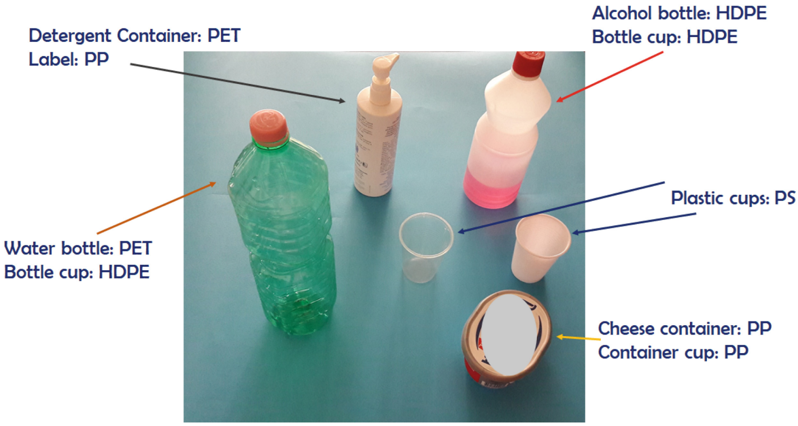

Fig. 1. Some plastic single use containers/items that can be found in post-consumer plastic streams. (PET: polyethylene terephthalate; PP: polypropylene; HDPE: high density polyethylene; PS: polystyrene)

4 Effect of Replacing Fine Aggregate with Plastic Waste of Different Chemical Nature on the Properties of Concrete

Multiple studies in literature illustrate the effects on the slump of concrete due to the introduction of plastic waste in replacement of aggregates. Ismail and AL-Hashmi [8] noticed that the values of slump of concrete mixes containing plastic waste (consisting of about 80% PE and 20% PS) tended to decrease with increasing the waste content. This reduction was attributed to the different shapes of the waste particles: some were angular while others had non-uniform shapes. Similar results were found also by Rai et al. [9], as illustrated in Fig. 2. The study stated that the sand in concrete was partially replaced by waste plastic flakes, without specifying the chemical nature of the polymer.

The same study [9] reported that fresh density of concrete decreased by 5.0%, 8.7% and 10.7% by replacing sand with 5%, 10% and 15% of plastic waste, respectively. This behavior can be attributed to the density of plastic waste that is much lower (by about 70%) than that of sand, resulting in a reduction of the fresh density of concrete. These results are in line with those reported by Ismail and EL-Hashmi [8]. Figure 3 illustrates the effect of an increase in the amount of plastic waste on the fresh density of concrete.

Referring to the effects on mechanical strength of concrete, Ismail and AL-Hashmi [8] found that the compressive strength decreased with increasing the quantity of plastic waste, irrespective to the curing age of concrete. This result, aligned with findings

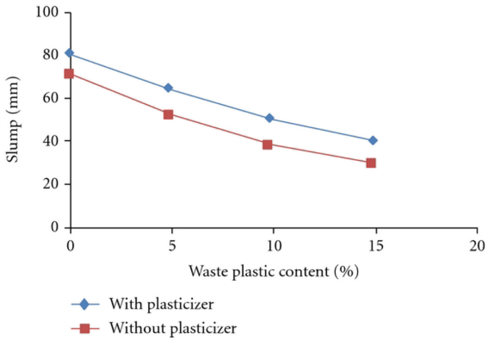

Fig. 2. Slump of concrete mixes with different % of plastic waste [reprinted with permission from reference 9].

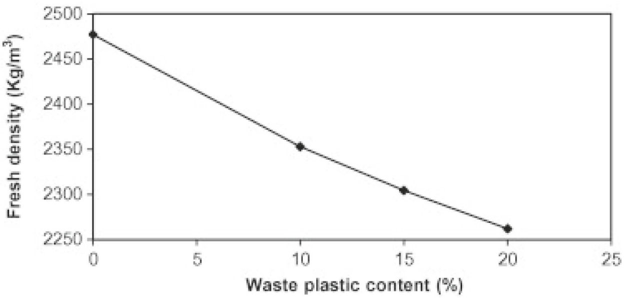

Fig. 3. Effect of plastic waste content on the fresh density of concrete [reprinted with permission from reference 8].

reported by other Authors [9], is largely attributed to the low adhesion strength developed between the plastic (PE and PS) particles and the cement paste. Similarly, Mustafa and co-workers [10] found that the compressive strength of the plastic-concrete decreased as the plastic content increased. Polycarbonate (PC) particles from industrial waste were used in this study. The decrease in strength was again mostly attributed to a low adhesion between the cement paste and polycarbonate aggregate, partly to the lower resistance and stiffness that characterize the plastic material. Figure 4 gives an example of how the compressive strength of concrete is influenced by an increasing addition of plastic waste to replace inorganic aggregates.

Passing to analyze the tensile strength properties, Rahmani et al. [11] studied the influence of the addition of PET particles, in quantities up to 15%, on the tensile strength of concretes based on two water-cement ratios, i.e. 0.42 and 0.54, respectively. The PET particles were obtained by grinding post-consumer bottles. A decrease in tensile strength was observed, again attributed to the limited adhesive strength between the plastic aggregate and the cement paste. Figure 5 presents the tensile strength values as a function of the percentage of plastic waste added to the concrete, as found in [11].

Albano and co-workers [12] analyzed the replacement of sand with PET, up to 20% by volume, in concrete with two values of the water-cement ratio, namely 0.50 and 0.60.

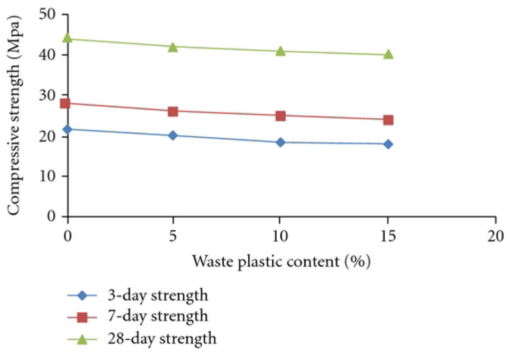

Fig. 4. Compressive strength of concrete as a function of the % of plastic waste added and the age of curing [reprinted with permission from reference 9].

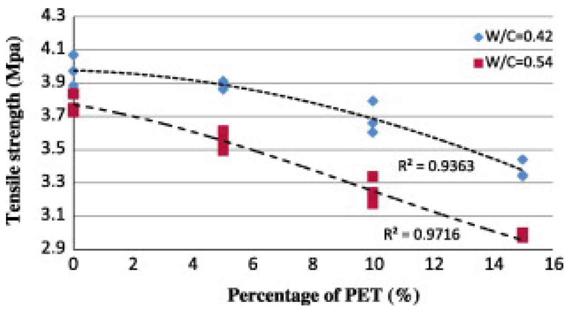

Fig. 5. Tensile strength at 28 days vs. the percentage of plastic waste, at two values of water/cement ratio [reprinted with permission from reference 11].

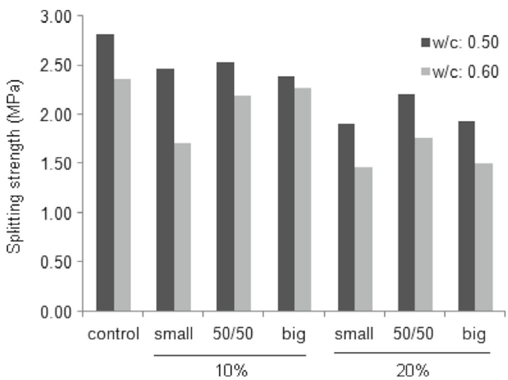

Fig. 6. Splitting tensile strength of Concrete-PET blends at different water/cement ratios [reprinted with permission from reference 12].

The average dimensions of the PET particles were 0.26 (small granules) and 1.14 cm (large granules); PET came from recycled-waste bottles. The Authors of the study found that a decrease in the splitting tensile strength at a water-cement ratio equal to 0.50 compared to the reference concrete, regardless of the size of the PET particles. The decrease in strength was more significant when the amount of ground PET reached 20%, attributed to the high porosity of the concrete at this high amount of PET. A very similar trend was also observed for a water-cement ratio of 0.60: the tensile strength values decreased compared to the control concrete, even more significant. Figure 6 presents the splitting tensile strength values as a function of the percentage of plastic waste added to the concrete, as found in [12].

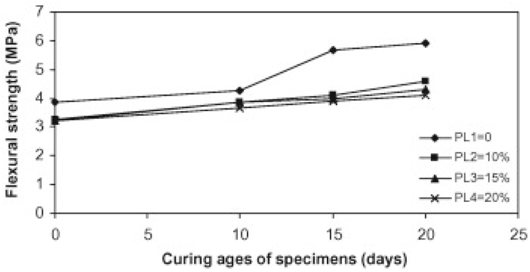

Fig. 7. Effect of waste plastic (content up to 20%) on flexural strength of concrete as a function of the age of curing [reprinted with permission from reference 8].

Finally, the effect of the addition of plastic waste on the flexural strength of concrete was evaluated by Ismail and AL-Hashmi [8]. These Authors found that the flexural strength of plastic waste-concrete decreased with increasing the content of polyethylene/polystyrene particles. These results are substantially in line with those found by Rai et al. [9]. Harini and Ramana [13] found that the flexural strength decreased by increasing plastic granules (PET, less than 4.75 mm in size) in place of fine aggregate, irrespective to the curing age. This result was again attributed to the low bond strength between the surface of the plastic particles and the cement paste. The effect of plastic waste on the flexural strength of concrete is summarized in Fig. 7.

In all the examples just illustrated, the replacement of the fine aggregate in concrete with post-consumer plastic particles, based on different polymers, led to a general decrease in the mechanical properties of concrete, except for the effect of fibrous plastic particles on flexural strength. This finding was attributed to the poor adhesion that develops at the interface between an organic material, i.e. plastic particles, and an inorganic one, i.e. cement paste. To solve this problem, several solutions have been proposed. A first possibility involves the use of plastic particles with specific shape, size and aspect ratio. Typically, plastic fibers act as a physical bridge capable of limiting the propagation of fractures in concrete. In [14], the Authors revealed that the geometry of the PET fibers can play a significant role in achieving good mechanical properties of concrete. For instance, fibers with variable cross sections produced a substantial improvement in compressive strength over straight fibers.

A second possibility involves the modification of the surface properties of the plastic particles so that they exert an adequate adhesive strength to the cement paste. This can be achieved through an appropriate functionalization of the surfaces of the plastic material, in order to increase the chemical interactions with the cement paste: this solution is more effective but also has higher costs. An example is illustrated in the work by Akçaözoğlu and co-workers [15]. The Authors investigated the possibility to modify the surface of waste PET exposing this polymer to selected bacterial strains, in order to improve its chemical affinity and adherence with cement paste. These experiments were successful: they found that the concrete produced with the waste PET exposed to a bacterial strain achieved greater compressive and flexural strength values with respect to concrete containing un-treated PET.

5 Recent Attempts to Reuse Disposable COVID-19 Masks in Concrete

The Covid 19 pandemic that spread across the globe in the last two and a half years (2020–2022) resulted in a huge entry into the environment of disposable personal protective equipment (PPE), especially face masks. The polymeric material mainly employed in the fabrication of disposable face masks is polypropylene, the most of masks being realized in non-woven fabric PP. Several researchers have proposed different solutions to reuse/recycle the billions of single-use masks continuously released into the environment; some of them suggested to reuse them as aggregate in concrete in the wake of what has been experienced in the last years with post-consumer plastics.

In this case, the issues that arise are even greater than those already analyzed. The face masks consist of different layers: they contain a metallic part (to tighten the mask on the nose) and rubber ear loops. The different materials must be separated by disassembling the mask. The second important issue is represented by the possible need to sanitize the used masks before using them in concrete. Both procedures, that is the separation of the various components and their sanitization, involve an increase in production costs, justified only by a considerable increase in the performance of the concrete. Scientific research is, however, progressing fast in the search for a solution to this alarming environmental problem.

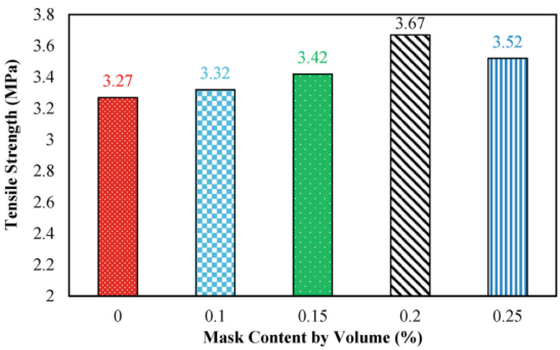

Fig. 8. Tensile strength at 28 days of concrete containing shredded face masks [reprinted with permission from reference 16].

The Authors of the study reported in [16] analyzed the effect of the addition of small amounts of shredded face masks on the mechanical properties of concrete. They found advantages in terms of improved compressive strength, indirect tensile strength (as illustrated in Fig. 8) and modulus of elasticity by including in concrete very small contents of masks, i.e. up to 0.2% by volume.

Encouraging results were recently found also by Ajam and co-workers [17], i.e. an increase in both compressive and flexural strength upon addition in cement mortars of up to 5% in volume of pieces of single use surgical masks.

6 Conclusions: Areas Where Further Research is Needed

The above overview has shown that post-consumer plastics can be effectively used as an aggregate in concrete, with multiple benefits for the environment [18, 19]. However, there are still many aspects to be clarified or deepened.

The presence of a random mix of different polymers in the plastic waste can lead to opposite behaviors in the properties of concrete. Future research should focus on identifying compositions able to achieve adequate concrete properties, regardless of the type of polymers contained in the waste, possibly playing on the shape and aspect ratio of plastic fibers.

New, low-cost and feasible methods must be developed to increase the adhesion at the interface between the plastic particles and the cement paste.

The high costs of these new building materials represent a limit to their wider use: it will be necessary to identify applications where high costs are justified by specific performances.

The literature is very lacking as regards the durability of plastic waste-concrete: this gap must be filled because, in addition to the mechanical performance, the durability of the concrete is an essential feature for their actual application.

Finally, there is an urgent need of standard codes and updated guidelines to reliably use polymer waste in concrete.

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