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Argamassas cimentícias com uso de agregado de polietileno tereftalato: uma revisão sobre sua sustentabilidade

Cement mortars with use of polyethylene tereftalate aggregate: a review on its sustainability

Morteros de cemento con agregado de tereftalato de polietileno: una revisión de su sostenibilidad

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Resumo

O alto consumo de produtos plásticos gera vários impactos, principalmente associados aos seus resíduos. Devido às suas características, as possibilidades de descarte desses resíduos são reduzidas, de modo que seu uso como subprodutos constitui a melhor solução para o gerenciamento desses resíduos. Nesse contexto, surgiram pesquisas que utilizam resíduos de produtos plásticos, como o polietileno tereftalato (PET) pós-consumo, como substituto do agregado natural em produtos cimentícios. A produção desses materiais pretende trabalhar em paralelo dois objetivos socioambientais: a redução do consumo de agregados naturais e a reutilização de resíduos plásticos em materiais de construção. Este trabalho apresentará dados relacionados a pesquisas sobre a produção de argamassas cimentícias com substituição parcial de areia natural por agregado leve de resíduos PET (ALRP) objetivando a realização do estado da arte contribuindo para o embasamento metodológico de futuras pesquisas acerca do

tema. Para isso, foram realizadas pesquisas sistemáticas nas bases de dados ScienceDirect, Web of Science e Scopus, através do uso de descritores, operadores lógicos e aplicação de restrição temporal. Além de apresentar os principais dados da pesquisa, será abordada a importância dos problemas associados ao tema e os parâmetros a serem atendidos por esse novo material ecológico, com base nos conceitos de construção sustentável.
Palavras-chave: Agregado leve de resíduo PET; Construção sustentável; Materiais de construção; Compósitos.

Abstract

The high consumption of plastic products generates several impacts, mainly associated with its waste. Due to its characteristics, the possibilities of disposal of this waste are reduced, so that its use as by-products comprises the best solution for the management of this waste. In this context, research has emerged that uses the residue of plastic products, such as post-consumer polyethylene tereftalate (PET), as a substitute for the natural aggregate in cement products. The production of these materials intends to work in parallel two socio-environmental objectives: the reduction of consumption of natural aggregates and the reuse of plastic waste in construction materials. This work will present data related to research on the production of cementitious mortars with partial replacement of natural sand by light aggregate of PET waste (ALRP) aiming at the realization of the state of the art contributing to the methodological basis of future research on the subject. For that, systematic searches were carried out in the ScienceDirect, Web of Science and Scopus databases, using descriptors, logical operators and temporal constraint application. In addition to presenting the main research data, an approach will be made on the importance of the problems associated with the theme and the parameters to be met by this new ecological material based on the concepts of sustainable construction.
Keywords: Waste PET lightweight aggregate; Sustainable construction; Construction materials; Composites.

Resumen

El alto consumo de productos plásticos genera varios impactos, principalmente asociados con sus residuos. Debido a sus características, las posibilidades de eliminación de estos residuos se reducen, por lo que su uso como subproductos constituye la mejor solución para el manejo de estos residuos. En este contexto, ha surgido una investigación que utiliza productos plásticos de desecho, como el tereftalato de polietileno (PET) posconsumo, como un sustituto

del agregado natural de productos de cemento. La producción de estos materiales pretende trabajar en paralelo con dos objetivos socioambientales: la reducción del consumo de agregados naturales y la reutilización de residuos plásticos en materiales de construcción. Este trabajo presentará datos relacionados con la investigación sobre la producción de morteros cementosos con reemplazo parcial de arena natural por residuos de PET de agregado ligero (ALRP) con el objetivo de realizar el estado del arte contribuyendo a la base metodológica de futuras investigaciones sobre el tema.. Para ello, se realizaron búsquedas sistemáticas en las bases de datos ScienceDirect, Web of Science y Scopus, utilizando descriptores, operadores lógicos y restricción temporal. Además de presentar los principales datos de investigación, se abordará la importancia de los problemas asociados con el tema y los parámetros que debe cumplir este nuevo material ecológico, basado en los conceptos de construcción sostenible.
Palabras clave: Agregado ligero de residuo de PET; Construcción sostenible; Materiales de construcción; Composicion.

1. Introduction

In recent decades, large volumes of natural resources have been used in industry, commerce and construction; in addition, human activities cause high rates of waste generation (Santos et al., 2020), causing soil, water and air degradation.

Sand is a natural aggregate formed from rock erosion over thousands of years. There are records of its use since the most remote times, as in the making of the blocks used in the Egyptian pyramids (Gavriletea, 2017). Today, it is the second most consumed natural resource on the planet, less only than consumption of water (Torres, Brandt & Liu, 2017).

Although sand is still a low-cost and widely available resource, the UNEP (United Nations Environment Program) warns of its future scarce. Sand extraction rates are exceeding the replenishment rate, being estimated that 40 to 50 billion tons of natural aggregates are extracted each year, with more than half of that volume consumed by the construction industry (United Nations Environment Program [UNEP], 2019). United Nations Environment Program (UNEP) (2019) also confirms the importance of the volume of natural resources used in the production of cementitious materials - such as concrete and mortar, about 65% of the total produced is composed of natural aggregates.

Teriftalated polyethylene (PET) is one of the most used polymers in the world (Vidales, Hernández, López, Flores & Hernández, 2014). One million plastic bottles are purchased every minute, with the forecast that by 2021 that number will increase by 20% (Laville & Taylor, 2017). Due to the overuse of this material, the problem caused by its waste grows.

In search for sustainable solutions for PET waste, in last two decades research has been developed using the waste as a component of concrete and mortar (Almeshal, Tayeh, Alyousef, Alabduljabbar & Mohamed, 2020; Mohammed & Rahim, 2020). The objective of this work is carry out, through the literature review, an approach on the use of waste PET lightweight aggregate (WPLA) as substitute for sand in cementitious mortar, using as parameter the sustainability of the material through its performance and durability. For that, were selected scientific works disseminated in media worldwide publications - ScienceDirect, Web of Science e Scopus, and produced in the last ten years.

2. The Plastic and its Impacts for Society

Plastic is considered one of the most important innovations of the 20th century (Saikia & Brito, 2012). Due to its durability, versatility and low cost, its production grows around 9% per year (Da Silva, Brito & Veiga, 2014), reaching a global production of 330 million tons in 2016, preview a doubling of this value in the next 20 years. The plastics that dominate the most common applications are: polyethylene (PE), polypropylene (PP), polystyrene (PS) and polyethylene terephthalate (PET) (Lebreton & Andrady, 2019).

Although these materials have several convenient characteristics, such as long service life, flexibility, low density and better thermal properties, it generates major socio-environmental impacts (Thomas & Moosvi, 2020). Currently, about 4% of the fossil fuel extracted is used in the manufacture of plastic (Lebreton & Andrady, 2019), in addition, they are composed of several toxic chemicals, being a polluting agent for soil, air and water. Due to its non-biodegradable nature, the disposal of its waste in landfills means to preserve a harmful material for hundreds of years (Saikia & Brito, 2012), making it necessary to design new possibilities for disposal of this waste.

2.1 Environmental impacts

Plastic particles smaller than 5 mm are called microplastics, and these have attracted special attention from scholars due presence in several places around the globe (Ostle, Thompson, Broughton, Gregory, Wootton & Johns, 2019). The presence of microplastic — polyethylene teriftalate, polypropylene, polyethylene was found in 94% of table salts tested in research worldwide. Lee, Kunz, Shim and Walther (2019) notes that, on average, table salts contain 140.2 microplastic particles per kilogram of product, concluding that humans annually ingest an average of 525 microplastic particles just in salt. However, there is still no consensus on the existence of health risks and the amount of ingestion of microplastics that can be considered harmful (Lee, Kunz, Shim & Walther, 2019).

Besides food contamination, research revealed that microplastics can affect human health through inhalation. In China, it was found that on average one child inhales 17,300 nanograms per kilogram of body mass of PET microplastic fiber in just one day (Abbasi, et al., 2019). According to Liu, Wang, Wei, Song and Li (2019), microplastics suspended in the atmosphere (SAMPs) can represent a threat to human health because they can direct contact with respiratory organs resulting in chronic diseases. In that same study, it was found that during June 2019 in Shanghai, the majority of SAMPs — 51% of the total, consisted of fragments of polyethylene terephthalate (PET).

Plastics also become prevalent in the ocean environment (Ostle, Thompson, Broughton, Gregory, Wootton & Johns, 2019). Today it is believed that 90% of waste floats in the oceans are consisted of plastic waste. According to the United Nations (UN) (2017), more than 8 million tons of plastic reaches the oceans each year, being forecast that by 2050 there will more plastic materials than fish in the oceans and that 99% of sea birds will have ingested the residue of this material.

Contamination with macro and microplastics in aquatic habitats reduces the growth rate, fertility and life expectancy in animals, in addition reducing the body's defenses (Trotter, Ramsperger, Raab, Haberstroh & Laforsch, 2019). It was detected through research by Tetu et al (2019) that exposure to plastic waste impairs the growth and photosynthetic capacity of marine *Prochlorococcus*, considered the most abundant photosynthetic organism on earth and an important contributor to the production of oxygen and consumption of planet's carbon.

2.2 Polyethylene tereftalate (PET)

Polyethylene terephthalate (PET) is one of the most important plastics used today (Kim, Yi, Kim, Kim & Song, 2010). Due its properties such as lightness and ease of handling and storage, it is used for making bottles and packaging for most edible products (Frigione, 2010). It is characterized as a material of high resistance, lightness and low permeability to gases such as CO2 (Reis & Carneiro, 2012), in addition, it has great durability and low production cost, generating a material with excellent cost-benefit (Ge, Yue, & Sun, 2015).

Since the 1970s, PET packaging production has grown steadily (Reis & Carneiro, 2012). In 2014 the world production of PET was 42 million tons (Kim, Yi, Kim, Kim & Song, 2010), and this number is expected to grow to 72 million tons in 2020. Regarding the consumption of PET bottles, there was an increase of 300 billion units in the year 2000 to 480 billion in 2016, and is expected that number increase to 583 billion in 2021 (Benavides, Dunn, Han, Biddy & Markham, 2018).

Given this scenario of increasing consumption rates of PET products, associated with its need for a long period for degradation - more than one hundred years due its high resistance to atmospheric and biological agents, becomes the most effective solution for the problem of the destination of waste PET its reuse for the production of new materials (Silva et al., 2005; Li, Ling & Mo, 2020). With this aim, the possibility of reusing these residues in construction materials appears as an excellent possibility, and in addition, it allows the reduction of the use of natural resources as raw material.

3. Sustainable Constructions and its Parameters

The world population more than doubled since 1950, with an estimated 9.8 billion people in 2050 (United Nations [UN], 2017). This demographic growth trend associated with urban migration results in an increase in demand for buildings (Luangcharoenrat, Intrachooto, Peansupap & Sutthinarakorn, 2019). On the other hand, it is known that after the food industry, construction is the sector that most demands raw materials in the world (Berge, Butters & Henley, 2009), in addition to consuming 35% of the energy produced worldwide and being responsible for the release of 40% of carbon dioxide from terrestrial atmosphere (United Nation Environment [UN Environment] & International Energy Agency, 2017), so that Da Silva, Gama, Salles and Braga (2019) emphasizes that no society can achieve environmental sustainability without major changes in the construction industry.

In this context appear the sustainable constructions, which are infrastructures that seek the application of methods and processes in order to generate the least socio-environmental impact (John, Clements-Croome & Jeronimidis, 2005; Medineckiene, Zavadskas, & Turskis, 2011). Agenda 21 lists materials innovation as an objective in the development of sustainable buildings (Du Plessis, 2001). With this focus, the innovation of materials from the substitution of natural resources by products of recycled waste supports the improvement of this sector, reducing the impacts of new construction materials (Burroughs & Růžička, 2019).

A parameter for sustainable construction is durability, because there is a strict link between durability and sustainability of a product (Nicolella, Landolfi, Pino & Scognamillo, 2019). In some languages like Dutch, Finnish or Romanian the term sustainable is translated as durable (Bourdeau, 1999). In view of the close relationship between terms, the sustainability of construction can be improved by increasing the durability of materials (Malholtra, 2002), since durable materials require less frequent replacement and require less raw materials, in addition to producing less waste in landfills throughout their useful life. Durability is not an intrinsic quality of material, simple changes in the compositions or design of the materials can increase its useful life without necessarily increasing its environmental load (John, Agopyan, & Sjostrom, 2002).

Another criterion for evaluation construction materials is its performance (Sinha, Gupta, & Kutnar, 2013), due sustainable construction involves the analysis of functional performance of its components during the life of building (John, Clements-Croome & Jeronimidis, 2005), that is, it is necessary to ensure that the building systems perform satisfactorily the functions for which they were designed.

4. Methodology

In this research called state of the art, the level of knowledge found at a given moment is analyzed, and it can also be called the state of knowledge (Ferreira, 2002). According to Soares (1987), the state of knowledge on a theme is indispensable in the process of evolution of science, so that the information and results already obtained are verified, allowing the identification of duplications or contradictions and the existence of gaps and biases. It has a bibliographic and descriptive character of academic productions, and its functions are both qualitative — through the description of methods and processes of production and evaluation of materials, and quantitative — presenting the data resulting from technical tests (Ferreira, 2002).

For the preparation of this review, scientific articles from the ScienceDirect, Web of Science and Scopus databases were used. Searches were made on titles and keywords using descriptors, Boolean operators and time constraints from the past 10 years. The abstracts and materials used in the articles obtained were analyzed and then those that deal with the production of cementitious mortars with replacement of natural sand by waste PET lightweight aggregate (WPLA) were selected, excluding research using fibers, resins or other types of interference.

At the end of the described process, six articles were obtained in which were analyzed the materials used, production and evaluation procedures of samples and physical results — consistency of fresh mortar, apparent density of the hardened mortar, ultrasonic testing, mechanical results — resistance to compression and flexion and durability.

5. Results and Discussion

From this section, the main materials, procedures and results identified in the selected researches will be presented.

5.1 Binder material and aggregate natural

In research analyzed, river sand was used, as usually do in constructions. Safi et al. (2013) made use of the combination of sand in the range between 0-5 mm, together with limestone filler. Detomi et al. (2016) e Da Silva et al. (2014) besides select specific size range for natural sand, the PET particles that served as substitute for sand were also used in the same size range, so that the aggregates' granulometric curve remained the same in all compositions. The specific gravity and bulk density of the natural aggregate are about 2600 kg / m^3 and 1700 kg / m^3, respectively (Choi et al., 2009; Hannawi et al., 2010; Safi et al., 2013; Da Silva et al., 2014; Detomi et al., 2016; Gouasmi et al., 2016).

All the researchers used portland cement as bonding material. Safi et al. (2013) and Gouasmi et al. (2016) used portland limestone cement with strength class 42.5 (CEM II / A-L 42). Da Silva et al. (2014) used portland limestone cement with strength class 32.5 (CEM II / BL 32.5), while Hannawi et al. (2010) the common portland cement (CEM I). The specifics gravity's are between 2,975 and 3,150 kg / m^3 (Choi et al., 2009; Hannawi et al., 2010; Safi et al., 2013; Da Silva et al., 2014; Detomi et al., 2016; Gouasmi et al., 2016).

5.2 Waste PET lightweight aggregate (WPLA)

Generally the WPLA is come from waste of industrial processes of PET industry or products from shredder machines of PET plastic. Choi et al. (2009) realize a specific treatment to obtain the WPLA. This author uses a procedure for cutting PET particles (5-15) mm and doing later mixing of this material with river sand (diameter less than 0.15 mm) applying a rotation of 30-50 rpm and temperature (250 ± 30) °C. After cooling material, the fraction retained in the 0.15 mm sieve is selected and used for the production of mortar samples (Figure 1).

Figure 1: WPLA obtained after treatment and used for sample production.

Source: Choi et al. (2009).

Hannawi et al. (2010) used WPLA from PET waste of industrial process (Figure 2). The sample has a maximum dimension 10 mm and 71.4% particles smaller than 5 mm. Its specific gravity and bulk density is 1,358 and 547 kg / m^3, respectively.

Figure 2: WPLA from PET waste of industrial process.

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Source: adapted from Hannawi et al. (2010).

Safi et al. (2013) obtained the WPLA (Figure 3) through processing in industrial recycling machines of waste from bags manufacturing. Its maximum dimension is 4 mm, with 80% of sample less than 3 mm. The material has specific gravity and bulk density of 960 and 510 kg / m^3, respectively.

Figure 3: WPLA obtained through processing in industrial of waste from bags manufacturing.

Source: Safi et al. (2013).

Da Silva et al. (2014) used two processes for obtaining the WPLA. The first one is identified as PF (PET flakes), it was produced by shredding the materials of PET bottles in particulates with size between (1 – 4) mm. In the second process, to obtain the sample called PP (PET Pellet), in addition to grinding, a thermal process was carried out. For the composition of mortars, a grain size range between (1 – 2) mm was used. The specific gravity and apparent density of the residues are 1,280 and 474 kg / m³ for PF and 730 and 1,303 kg / m³ for PP, respectively.

Gouasmi et al. (2016) obtained the recycled aggregate through heat treatment followed by gradual cooling of PET bottles, in order to assign hardness to the material. Soon after, the material was subjected to industrial milling that generated different granulometric fractions, including the range (0 – 3) mm that was used in the production of the mortars.

5.3 MIX design and proportion of mortars

The researches carried out the mixtures of the materials specified in section 4.1 and according the quantity indicated in Table 1.

Table 1: Material rates in mortar mixes.

Ref.	cement: aggregate (weight)	water/ cement	Replacement of natural aggregate with WPLA (% - volume)	Filler/ cement	Additive (% ocm)
Choi et al. (2009)	1:2.44	0.6	0, 25, 50, 75 e 100		
Hannawi et al. (2010)	1:3	0.5	0, 3, 10, 20 e 50		
Safi et al. (2013)	1:2.06	0.42	0, 10, 20, 30 e 50 (weight)	0.1	1.59
Da Silva et al. (2014)	1:6.13	1.35	0, 5, 10 e 15		
Gouasmi et al. (2016)	1:2.03	uninformed	25, 50, 75 e 100		

Source: authors.

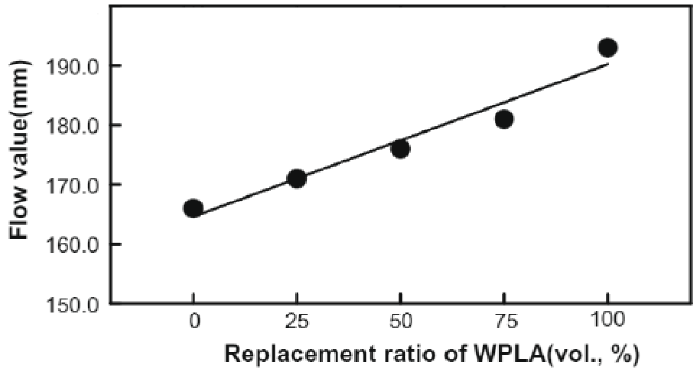
The mixing procedures were done manually or mechanically, using specific equipment and adopting procedures of respective standardizing organs. Subsequently the mixtures were placed in prismatic or cylindrical molds, for making the test samples, which are in most cases removed from the mold after 24 hours and curing process performed for 28 days with controlled temperature and humidity.

Some researchers used the consistency of fresh mortar to fix the water/cement ratio, attending normative parameters or adopting limits of the mortar spreading. They used values between 85 and 173 mm (Da Silva et al., 2014; Gouasmi et al., 2016).

5.4 Consistency of fresh mortar

The results found identify the increase in the flow value of mortar in function of the increment of WPLA in a linear way (Figure 4). According to Choi et al. (2009) this tendency occurs due reduces internal friction between mortar and the WPLA caused by shape of the PET aggregate (Safi et al., 2013).

Figure 4: Mortar flow value in function of WPLA rate.



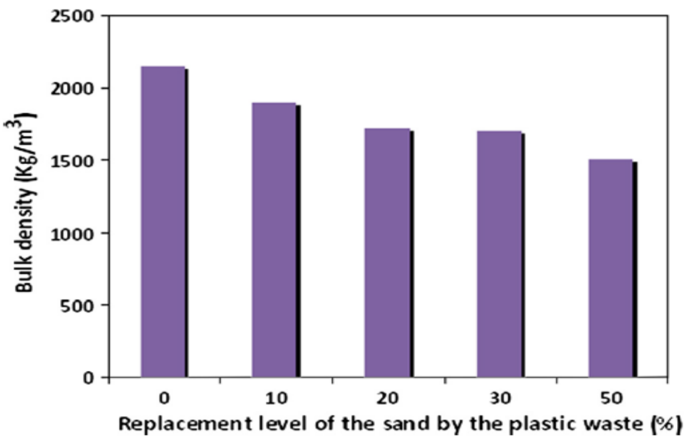
Source: Choi et al. (2009).

Da Silva et al. (2014) found the replacement of up to 15% of natural sand by WPLA did not significantly influence the consistency of the mortar, obtaining through same values of water/cement ratio same consistency in the different mortars with substitution of natural aggregate by WPLA .

5.5 Bulk density of hardened mortar

The values of bulk density of specimens at 28 days of age were determined, checking a reduction in density values in all mortars with substitutions (Figure 5). This reduction occurs because the density of the plastic aggregate is up to 70% lower than that of natural sand (Hannawi et al., 2010).

Figure 5: Bulk density as a function of the WPLA rate.



Source: Hannawi et al. (2010).

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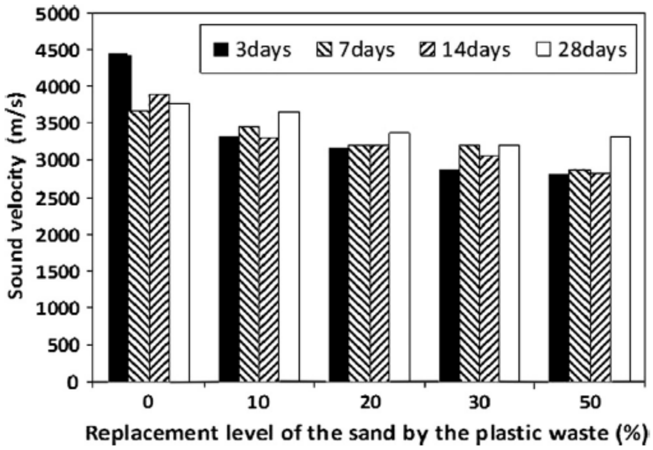
Detomi et al. (2016) found the lowest density values were obtained when there was a replacement of the coarse-medium sand strips, 30% and 50%, respectively, and medium-fine sand, 50% and 20%, respectively.

5.6 Ultrasonic test of mortar

A reduction in the ultrasonic pulse speed was observed in the mortar samples aged 3, 7, 14 and 28 days due to increase in the WPLA rate in the mortars (Figure 6). This result is attributed to the filling of all voids in material by cement hydration products (Safi et al., 2013).

Figure 6: Speed of the ultrasonic pulse as a function of the WPLA rate.



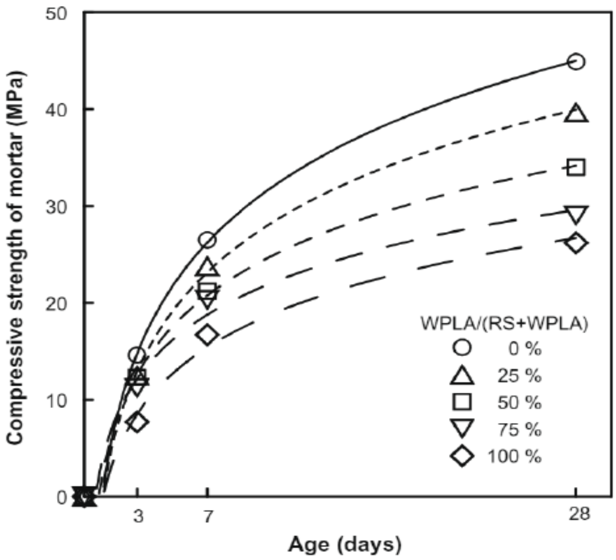
Source: Safi et al. (2013).

Da Silva et al. (2014) found a reduction in the modulus of elasticity due to the increase in WPLA in mortars, which is a consequence of reduction in the speed of the ultrasonic pulse checked by Safi et al. (2013).

5.7 Compressive strength of mortar

It is possible to verify the increase in strength as a function of the age of mortar, however, a reduction as a function to the increase in the WPLA rate in the mortar (Figure 7). Mortar with replacement 100% of natural sand by WPLA showed a 42% reduction in its strength at 28 days compared to the reference sample (Choi et al., 2009). In addition to these ages, Safi et al (2013) verified resistance at 14 days, identifying the same trend of decreasing of resistance, showed a 33% reduction with a 50% replacement rate.

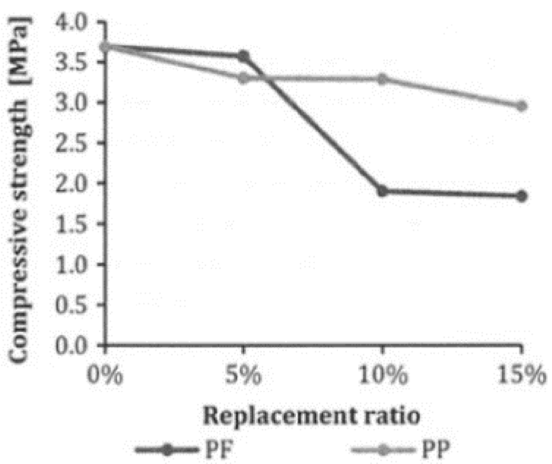
Figure 7: Compressive strength as a function of age at break and of replacement rates of sand by the WPLA.



Source: Choi et al. (2009).

Hannawi et al. (2010) still notes that the failure obtained during the rupture of mortar becomes more ductile due the presence of plastic in mixture. In addition, Da Silva et al. (2014) observed a clear difference between the results of the mortar with addition of PP (PET Pallet) and PF (PET Flakes), being possible to observe the comparison of the results of compressive strength in Figure 8.

Figure 8: Compressive strength as a function of the rate of sand substitution by WPLA.



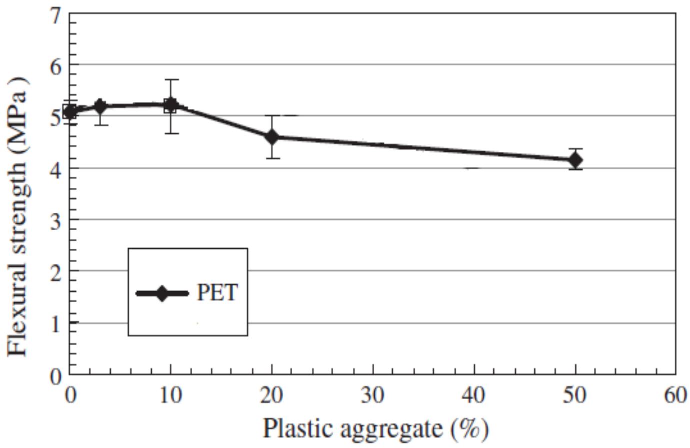
Source: Da Silva et al. (2014).

The figure 8 indicates a significant drop in the compressive strength of the mixture using PF (PET flakes) after substitution of 5%, possibly due to the difference in the physical form of the aggregates, since PF are deformable flakes with low resistance compared to PP (PET pellet).

5.8 Flexural strength of mortar

The tests indicated the variation in flexural strength as a function of the WPLA rate in the mortars (Figure 9).

Figura 9: Resistência a flexão em função da taxa de WPLA.



Source: adapted from Hannawi et al. (2010).

The figura 9 indicates with up to 10% replacement of natural aggregate by WPLA no occur significant change in resistance, however, from that replacement rate, reductions occur proportional to the increase in WPLA, reaching 17.9% reduction in the flexural strength of mortar with 50% replacement of sand by WPLA (Hannawi et al., 2010).

Comparing the results of resistance to compression and flexion, it is possible to observe that, unlike the compression test, there is no increase in ductility when a flexural load is applied, leaving a fragile behavior in the material

5.9 Mortar durability

Data associated with the durability of mortars using WPLA have been neglected so far. Information about it found only in the research by Da Silva et al. (2014) through the accelerated aging test, where the samples are submitted for 8 heating-freezing cycles and 8 humidification-freezing cycles. The effects of these processes were evaluated through visual analysis, adherence tests and water permeability tests. The test showed degradation in the mortar surface after the cycles, in addition to a reduction in the adhesion values and an increase in water permeability, possibly due to damage caused by the cycles causing expansion and retraction at microscopic level in the samples.

6. Final considerations

The objective of the research was achieved through the elaboration of the state of knowledge about the use of PET light aggregate residues (WPLA) as a substitute for sand in construction materials. Based on the concepts of sustainable construction and the results obtained in the analyzed researches (Choi et al., 2009; Hannawi et al., 2010; Safi et al., 2013; Da Silva et al., 2014; Detomi et al., 2016; Gouasmi et al., 2016) it is possible to conclude:

- The use of WPLA as a substitute in natural mortar sand becomes an interesting option to reconcile the reduction in the use of natural aggregates and the reuse of non-biodegradable waste;
- Mortars produced with substitution of sand by WPLA have more fluidity due to the reduction of friction between the paste and the WPLA, this increase is insignificant in increments of less than 15% of WPLA;
- There is a reduction in the bulk density of the mortar in hardened state in function the increase the WPLA rate in the mixes;
- There is a reduction in the speed of the ultrasonic pulse and, consequently, of the dynamic elasticity modulus of the mortars in function of increase in WPLA in mixtures;
- The compressive strength was reduced due to the increase in WPLA in mixtures; found it a reduction between 29% and 69% for a 50% replacement rate from sand by WPLA;
- Flexural strength has been reduced as a function of increase in the WPLA rate in mixture. A reduction between 18% and 40% of resistance was observed from the 50% replacement rate from sand by WPLA;
- The improvement in indices of deformability of the mortar with WPLA, generating a material with greater capacity to absorb impacts and mobility to expansions and retractions, thus reducing its cracking.

- There is evidence of a reduction in the absorption and adhesion performance of mortars using WPLA after aging cycles;

The ordering of the results described allows us to identify the need for improvement in deficient results, such as compressive and flexural strength, and the identification of gaps such as the analysis of the durability of mortars - made impossible by the scarcity of analyzes, application of few aggressive agents and a limited number of performance indicators, contributing to the advancement of science based on the knowledge already available in the scientific community.

It is suggested for future work to make samples with sand replacement rates for WPLA below 15% and to apply an accelerated aging test using UV radiation as a degradation agent.

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