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Review

Waste Plastic and Rubber in Concrete and Cement Mortar: A Tertiary Literature Review

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Abstract: In recent years, the addition of plastic and rubber waste to construction materials has been widely studied by the research community. This great interest can mainly be attributed to the achievable potential environmental and economic benefits, mainly deriving from the reduction of incinerated or landfilled wastes and the decrease of used raw materials. Several reviews have been published on the addition of polymeric waste materials in concrete and cement mortar mixtures, discussing properties, environmental and cost implications. However, there are not available studies that organize and analyses the knowledge presented in this review. For the scope, in this paper we present a tertiary study of previous relevant review articles from peer-reviewed journals, with the aim to provide an overview of the state of the evidence related to this topic and to highlight the main critical aspects and open issues. The overview provides conclusions drawn from the 33 included reviews finding different open issues on the theme regarding environmental performance, cost savings and impacts on the supply chain as well as long term health problem related to the use of waste plastic and rubber in concrete and cement mortar. For each open issue further research proposals are also suggested.

Keywords: green concrete; waste plastic; aggregate; fiber; sustainable building material; tertiary review

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1. Introduction

Concrete is the most widely used construction material next to water [1]. This is a mixture of cement, aggregate and water, which are components widely available on the market and at low cost [2]. According to the Global Cement Report [3], the global use of cement in 2019 reached 4.08 billion tons (an increase of 2.8% compared to the previous year). Most of the demand was concentrated in China (about 56%), which strongly influenced the market (+4.9% compared to 2018), followed by India. Excluding these two countries, the global market was unchanged compared to previous years (+0.3% compared to 2018). Aggregates are key elements in concrete and cement mortar, both due to the percentages present (aggregate occupies approximately 65–80% of the mixture) and because they determine to a good extent the properties of concrete both in a fresh and hardened state. Fibres can be added to the mixture to reinforce the cement matrix [4] and to overcome concerns related to the brittleness and poor resistance to crack initiation and growth in cement-based materials [5]. The increase in global demand has led to a consequent build-up in the raw materials necessary for its production. For this reason, considerable efforts have been made at international level to support the transition of the infrastructure and construction sector towards approaches capable of respecting the principles of sustainable development, reaching the triple bottom line requirements of sustainability: economic, social and environmental dimensions [6]. This is also important to achieve the Sustainable Development

Goals (SDGs) established by The 2030 Agenda for Sustainable Development [7]. Among the solutions adopted to promote the sustainability of the construction sector, the adoption of a circular approach to replace traditional linear paths is a widespread practice [8], in particular as substitutes of coarse and fine aggregates and fibres [9]. The use of by-products and waste as sources of secondary raw materials constitutes an approach with high potential [10]. For example, at European level, within the strategy for improving the efficiency of resources, waste is recognized as a possible substitute for raw material [11]. This offers a potential double benefit: reducing natural raw materials used for concrete production and replacing aggregates and fibres with waste materials, thereby helping to reduce the quantities to be disposed of in landfills or incinerators [12]. Figure 1 shows a list of possible waste materials used as alternatives in cement mixes.

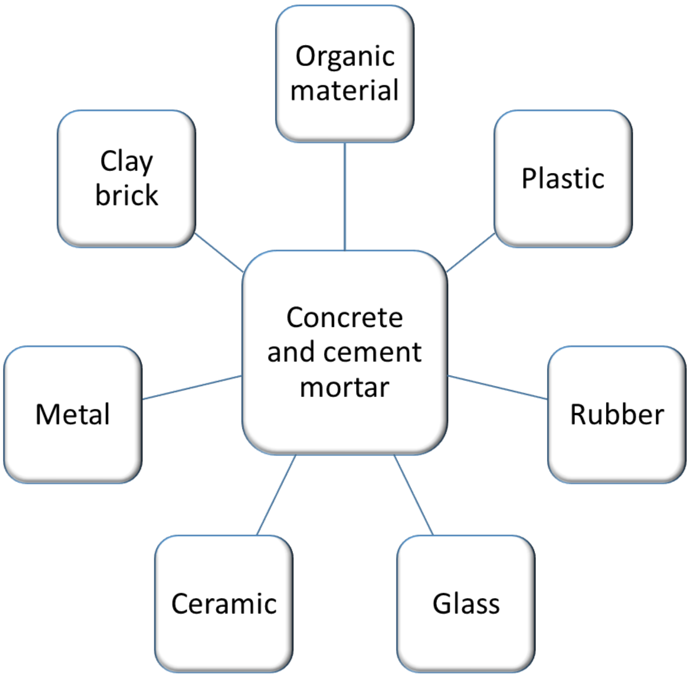


Figure 1. Some of the possible mixable waste materials in concrete and cement mortar.

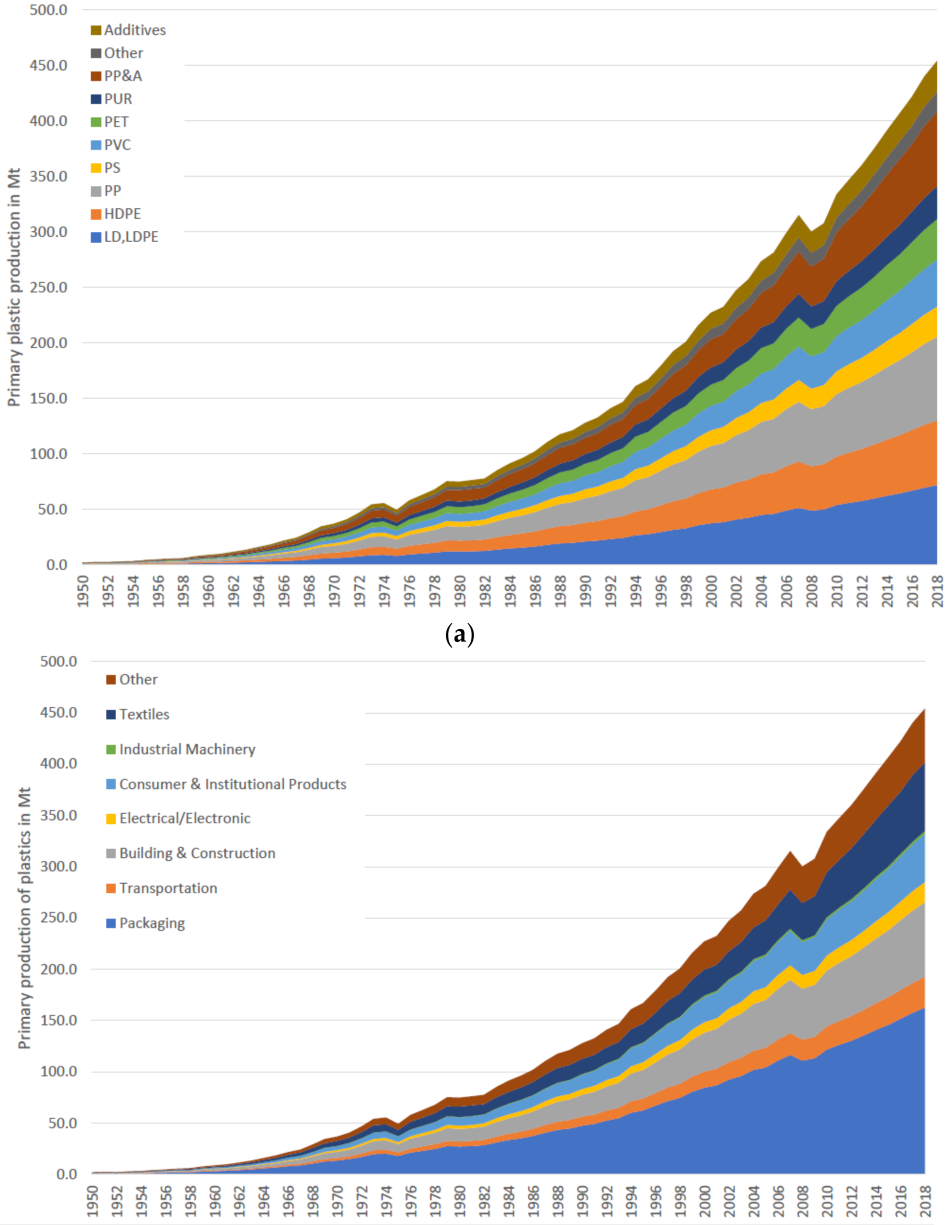
Among the different waste materials, plastics and rubbers are widely used in the construction industry [13]. In fact, compared to other waste materials, polymeric aggregates and fibres have several advantages, such as their excellent resistance to chemicals and their durability [14]. In addition, their use does not result in a loss of quality during the service cycle and, in some cases, improves the overall performance of the product, favouring the development of a large scientific literature that deals with this topic.

The high number of scientific studies and literature reviews related to the recycling of plastic and rubber waste, drove us to perform a tertiary study to provide an overview of the state of the evidence in that area. Moreover, our aim is to highlight the main related critical and open issues.

1.1. Benchmark of Plastic Waste

Globally, plastics are one of the most popular and widely used materials in daily applications, from domestic to industrial and service activities. Currently, more than 30 types of primary plastics are available and, given their combined use with different additives, there are potentially thousands. Almost all (97–99%) derive from fossil sources [15], while a limited number are bio-based plastics (1–3%) [16].

Figure 2 shows two important pieces of information that represent the reference benchmark on a global level: the trend from 1950 to 2018 in the global production of primary plastics and their use. The growth has continued over time, reaching over 450 Mt/year, as visible packaging is the main use for plastics, followed by construction. Unfortunately, for packaging purposes plastics become waste after a single use while in construction the technical life is higher [17]. Together, the two applications account for more than 50% of plastic manufacturing and use.



(**b**)

Figure 2. Global production of primary plastics (**a**) and their use (**b**), 1950–2018. From [18].

Currently, there are technological solutions that allow you to recycle almost any type of plastic with some barriers represented by technical, economic and logistic factors [18]. Furthermore, it is very common (over 90%) for plastics to be recycled only once or twice prior to their final disposal [17,19,20] meaning that landfill and incineration still represent the most widespread approaches globally (79%). The composition of recycling trend varies significantly between countries. The United Nations Environment Programme (UNEP) reports that in India the recycling rate has reached 60%, while it is 32.5% in the EU and 9.1% in the US [18].

Waste plastic in concrete and cement mortar is used in fine fractions (dust) or in coarse fractions (fibres or pellets) to replace natural aggregates or for reinforcement for improving mechanical and strength durability [21,22]. In particular, polyethylene terephthalate (PET), polyethylene, both high (HDPE) and low-density (LDPE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), acrylonitrile butadiene styrene (ABS), polycarbonate (PC) and polyamides (PA) are the most common plastics in this sector [23]. PET, PE, PP, PVC and PS are the most common plastics globally (over 69%) [17].

This ductility of waste plastics in construction is closely connected with their extremely wide availability at an international level.

1.2. Benchmark of Waste Rubber

Among plastic wastes, an important proportion is made up of elastomers such as rubber, mainly deriving from automobile, lorry and motorcycle tyres. It has been estimated, in fact, that about 30 million tonnes of natural and synthetic rubber are sold every year [24].

Of the annual total global production of rubber material, approximately 65% is used to produce tyres [25]. Moreover, several studies demonstrate that vehicle tyres are an important source of rubber dust in the environment. According to a recent research conducted by [26], more than 200,000 tons of tiny plastic particles are blown off the roads into the oceans every year. This large volume of waste rubber material is an environmental problem of great concern. Waste tyres pose several health and environmental risks, including fires, various health impacts and environmental contamination [27]. Moreover, their non-biodegradable properties and the presence of the so-called "vulcanization system" in rubber mixes make it difficult to recycle rubber waste or to reuse it utilizing the general methods employed for thermoplastic materials [28]. Over the years, several applications have been investigated for reusing waste rubber, for example as an alternative fuel in cement production [29] or as a subgrade fill for roads and embankments in geotechnical applications [30].

With regard to the construction sector, several studies have been conducted about using waste rubber in concrete as a partial replacement for aggregates and many researchers have looked at various ways to improve the bond performance of rubber particles and to enhance the mechanical and durability properties of rubber concrete [28]. Rubber waste is more commonly utilized in the form of fine and coarse aggregate, although there are also some usages as a fibre and binder [31].

1.3. Scope of Tertiary Review

A tertiary study aims to provide a very broad summary framework on a given topic through the study and analysis of the available literature reviews. Compared to a secondary literature review, which uses the primary research articles as sources of information, a tertiary study uses literature reviews to collect the information that is then analysed critically [32–34]. This approach indirectly allows the knowledge of a very large number of scientific publications to be capitalized upon.

To the best of our knowledge, there are no tertiary reviews dedicated to the study of waste plastic in concrete and cement mortar, despite the extensive literature available. Using a part of the title ("plastic in concrete") as keywords for a preliminary search of the ScienceDirect database, almost 85,000 articles were selected, of which over 3000 are review articles. It is interesting to underline how the number of contributions has increased significantly over the past 10 years, going from around 2000 articles/year in 2010 to over 6700 in 2019. Also, by refining the search, and using the words "waste" and "recycled" in the research, the volume of papers available is always significant (almost 22,000 and over 12,600, respectively).

With the aim of organizing all this knowledge and closing the gap of the lack of a tertiary review, the authors decided to study the review articles that dealt with the "waste plastic in concrete and cement mortar", presenting a structured review of the main contents and available priority aspects.

Three research questions were chosen to characterize the purpose of the assessments conducted through this study:

A1. What is the state of the art of knowledge?
A2. What are the most widely used plastic and rubber waste materials and the stated properties?
A3. What are the current critical aspects and open issues?

2. Methodology

2.1. Material Collection and Selection

To structure a successful literature review, with clear objectives and effective analysis methodologies, an operational protocol was applied to guide the material collection (Table 1) and selection (Table 2).

Table 1. Operational protocol for the material collection.

A	**Research questions**		-	-	
-	-	**A1.**	What is the state of the art of knowledge?		
-	-	**A2.**	What are the most used plastic and rubber waste materials and the stated properties?		
-	-	**A3.**	What are the current critical aspects and open issues?		
B	**Database**		-	-	-
-	-	**B1.**	ScienceDirect	-	-
-	-	**B2.**	Scopus	-	-
C	**Collection criteria**		-	-	
-	-	**C1.**	Journal	All	-
-	-	**C2.**	Year	All	-
-	-	**C3.**	Article type	Review	-
-	-	**C4.**	Date of search	December 2020	-
D	**Keywords**		-	-	
-	-	**D1.**	**Group A**	**Group B**	-
-	-	-	1-Concrete	a-Plastic	-
-	-	-	2-Aggregate concrete	b-Waste recycling	-
-	-	-	3-Green concrete	c-Recycled plastic	-
-	-	-	4-Sustainable concrete	d-Ecofriendly	-
-	-	-	5-Cement	e-Waste plastic	-
-	-	-	-	f-Systematic literature review	-
-	-	-	-	g-Narrative literature review	-
-	-	-	-	h-Critical review	**-**
-	-	-	-	i-Tertiary study	**-**

E					**Keywords research results (ScienceDirect/Scopus)**					
-	**-**	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**i**
-	**1**	3065/450	1936/194	1012/31	57/5	1395/58	5298/156	856/17	9923/385	1049/5
-	**2**	1101/46	958/115	554/21	20/0	661/21	1397/4	168/0	2588/35	310/0
-	**3**	1248/14	1101/26	536/6	39/0	711/11	1911/0	245/0	3549/8	436/0
-	**4**	1635/19	1546/64	760/11	44/0	984/11	2381/8	431/0	4660/34	512/0
-	**5**	3212/35	2005/65	1062/14	71/0	1457/13	2426/0	159/0	5845/34	994/0

The research in this review was conducted using ScienceDirect and Scopus without any restrictions on the journal or on the year of publication.

Two main groups of keywords were formed. Group A identifies the main reference issue of this paper and Group B reflects the study's specialization. By combining the two groups, 45 keywords were obtained and applied to the ScienceDirect and Scopus databases.

The collection of papers returned a very large number of articles, particularly from the ScienceDirect database and especially for the keyword combination "concrete" and "critical review".

According to the results of the material collection, papers were selected through the phases reported in Table 2. Each one analyses the contents of the review articles in greater detail, selecting only those that deal with the use of recycled plastic materials as an integrated material in the production of cement aggregates. Only a full-text assessment allowed the selection to be concluded, rejecting all the review papers not relevant to the theme chosen by this work and not useful for answering the research questions.

Table 2. Operational protocol phases for the material collection.

E	**Identification**			
	Analysis of titles and highlights			
F	**Screening**			
	Duplicate screening and abstract assessment			
G	**Eligibility**			
	Article is a review Article treats cement as the main product Article describes the use of recycled plastic materials as aggregates			
H	**Included**			
	Full text assessment			
I	**Number of articles selected**			
		ScienceDirect	Scopus	Total
		24	9	33

Overall, 33 review articles were found to comply with the objectives of this paper after applying the entire operational protocol.

In addition to the results of the operation protocol, browsing other known references and tracking down references in the selected papers (backward snowballing), other contributions were identified (Table 3).

Table 3. Final review articles selected.

From Operational Protocol
29
From browse approach
2
From snowball methods
2
Total
33

2.2. Material Analysis

In order to answer the research questions, the material analysis has been structured using the relevant aspects reported in Table 4.

The descriptive analysis (Group I), responding to Question A1, schematically describes the main descriptive aspects of the selected review articles. Year and journal contextualize the paper from a temporal point of view and its location within the scientific literature (since it responds to the specific aims and scope of the journal that published it). Country indicates the geographical area of origin of the corresponding author. Since the review articles critically analyse different research papers, the indication of the number of articles supports the definition of the reference framework described by each article.

Groups II and III describe the materials used, their applications and their properties. Thus, Question A2 is satisfied. Finally, Groups IV and V provide a picture of the still open problems and possible areas of intervention, thereby responding to Question A3.

Table 4. Material analysis structure.

I		Descriptive Analysis
I.1	-	Year
I.2	-	Journal
I.3	-	Country
I.4	-	Number of publications
II		**Category analysis**
II.1	-	Type of plastic waste
II.2	-	Use: aggregates and fibres
II.3	-	Applications
III		**Stated properties**
III.1	-	Physical and mechanical properties
IV	**Critical aspects**	-
IV.1	-	Main critical aspects
V	**Open Issues**	-
V.1	-	Main open issues

3. Results and Discussions

The results described below provide an assessment of the collected papers with respect to each relevant aspect reported in Table 4. The discussion of the results aims to answer the identified research questions.

3.1. Descriptive Analysis

The first review paper was published in 2008 by Siddique et al. [35], while most of the other articles are concentrated in recent years, in particular from 2016 onwards (84% of the total), as reported in Figure 3.

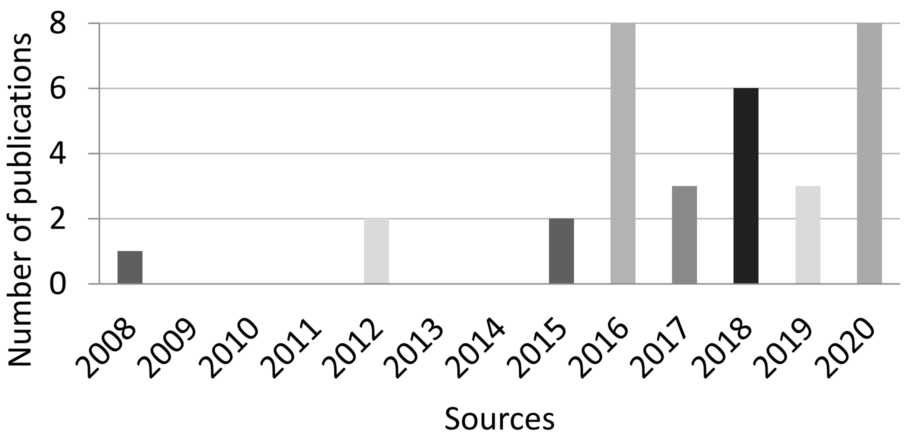


Figure 3. Number of publications per year.

The selected literature reviews are published in 17 different journals, with a strong concentration in Construction and Building Materials (about 35% of the articles analysed). The rest are distributed almost homogeneously among all the other journals. Figure 4 provides an overview of this situation, where the "other" category includes 12 different journals, each with one publication selected. The geographical distribution (Figure 5) involves 15 different countries, with a strong concentration in Asia and Europe. This evidence is in line with statistics related to: (i) the total plastic waste generation by country, which shows that China produces the largest quantity of plastics (nearly 60 million tonnes per year); (ii) mismanaged plastic waste, indicating that India most inadequately disposes plastic waste [17].

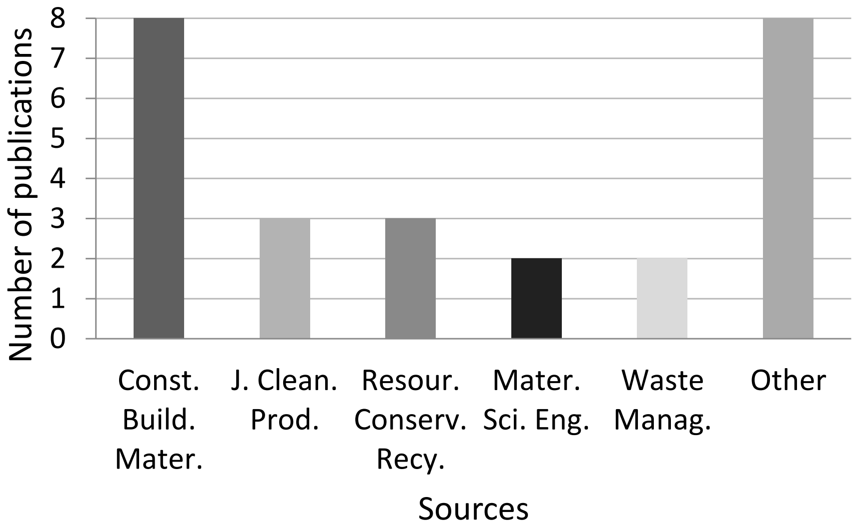


Figure 4. Number of publications per journal.

Figure 5. Geographical distribution of studies divided by reference areas.

3.2. Category Analysis

The category analysis defines the characteristics of the numerous types of plastics used in concrete and cement mortar, the dimensions of the samples used, as well as their applications. These characteristics described by the reviews analysed are summarized in Table 5. Almeshal et al. [23] provide a very broad picture of the plastics used in concrete and cement mortar, analysing 12 different types. This study, which analyses 103 papers, describes the use of recycled plastic aggregate as fine aggregate in cementitious composites and its impact on physical and mechanical properties, and durability. Also, the benchmark described by Mercante et al. [36] is very comprehensive, with 10 types described. These results derive from the analysis of 45 review papers referring to the addition of recycled plastic to concrete and mortar. The results clearly show that PET represents the type of plastic most studied in the literature: 78% of the authors analysed describe its use as a material added to cement and mortar. PP, rubber and tyres follow, described by 50% of the authors analysed.

Several authors focused their review on the mix in concrete and cement mortar of PET in the form of aggregates [37] and fibres [38,39] or both dimensions [40,41], highlighting the different properties of the final products. PET and PP are widely used thanks to their numerous possible applications, such as packaging for liquids and for food products (e.g., crisps or ice cream). In the case of tyres and other rubber goods, Mohajerani et al. [42] and

Roychand et al. [28] report that 1.5 billion waste tyres are generated annually and identify the sectors of civil and geotechnical engineering as key sectors of use.

The dimensions of the plastic samples that are used in concrete and cement mortar, according to Novotny et al. [43], can be divided into four categories, as shown below:

A. Dust: size up to 1 mm
B. Flakes: size of 1–10 mm
C. Pellets: size of 10–25 mm
D. Fibres: length of 25–50 mm

Fibres represent the dimensional structure most frequently analysed and described in the review articles selected by this study, with approximately 78% of the authors analysing them. Among polymer fibres, PP fibres have attracted the most research attention, because of their lower cost and simple processing compared with those of PE and PVA fibres [5]. Dust follows, although with almost halved percentages (about 43%). It is evident that the two extreme categories (fine plastics and larger fragments) represent the forms of greatest interest.

Several studies [5,23,35,43–47] describe the use of plastics across all possible identified dimensions.

Finally, from the point of view of their possible applications, concrete admixture represents the main use. According to these authors, a polymeric waste concrete potentially has several practical applications, such as concrete paving blocks and hydraulic structures, thanks to a higher abrasion resistance than conventional concrete [37,40].

Other authors also describe further possible uses in the construction and infrastructure sector, for example within the mixture that forms asphalt [48] and in bricks [36,49]. The possible applications indicated by many authors are not very thorough or precise, indicating their application for a wide range of uses relating to the construction and infrastructure sector.

When specified, the main source of plastic waste comes from the food industry, mainly beverage and food containers, followed by bags and other household plastics. Only two of the selected reviews [50,51] consider the plastic deriving from electric and electronic waste (e-plastic).

Table 5. Results of the category analysis.

Nr	Reference	Polymers Types	Waste Sources	Dimensions	Applications
1	[44]	PP, PET	bottles, bags, unspecified	A, B, C, D	lightweight concrete
2	[45]	PE, LDPE, PP, PET	bags, unspecified	A, B, C, D	self-compacted concrete
3	[23]	HDPE, LDPE, PET, PP, PVC, PS, EPS, HIPS, ABS, PC, MM, rubber	bottles, beverage containers, food containers, other household plastics	A, B, C, D	concrete, lightweight concrete, mortar
4	[50]	PET, e-plastic	bottles, electronic industry, unspecified	A, B, C	concrete, mortar
5	[52]	PET, PVC	bottles, beverage containers	A, D	admixture to concrete
6	[53]	virgin plastic, LDPE, HDPE	packaging, electronic industry, automobile residues	C, D	admixture to concrete, asphalt
7	[46]	PET, PVC, HDPE, GFRP, PUR, PC, PE, PP, PVA	bottles, bags, boxes, unspecified	A, B, C, D	self-compacting mortar and concrete, self-compacting lightweight concrete, self-compacting high-strength concrete

Table 5. *Cont.*

Nr	Reference	Polymers Types	Waste Sources	Dimensions	Applications
8	[40]	PET	unspecified	D	unsaturated polyester resin concrete
9	[41]	PET	bottles	D	admixture to concrete
10	[38]	PET	bottles	D	admixture to concrete
11	[54]	HDPE, PET, PVC, EPS, GFRP, virgin plastic	bottles, beverage containers, food containers, other household plastics	A, B, D	admixture to concrete
12	[31]	PET, EPS, PP, PO, PS, PE, rubber	bags, unspecified	A, B, C	admixture to concrete
13	[9]	PP, rubber	unspecified	D	Fiber-reinforced mortar
14	[49]	PET, unspecified	unspecified	B, C (unspecified)	concrete blocks
15	[36]	HDPE, LDPE, PET, PP, PVC, PS, PUR, MM, PA, rubber	unspecified	B, D	mortar and concrete composites, bricks, panels, subfloors
16	[48]	PE, PET, PP, PUR, PA, rubber	plastic bottles, tyres, textile industry, bag manufacturing	D	asphalt, fibre-reinforced concrete, concrete, lightweight concrete, mortar
17	[42]	rubber	tyres	A, B, C	admixture to concrete
18	[55]	PA, PET, PP, PUR	unspecified	D	admixture to concrete
19	[43]	PE, HDPE, PET, PP, PVC	bottles, rubbish bags	A, B, C, D	admixture to concrete
20	[56]	rubber, PET	bottles, tyres	A, B, C, D	admixture to concrete
21	[14]	PA, PET, PP, PVA, PUR	unspecified	D	admixture to concrete
22	[5]	PP, PE, PVA	unspecified	A, B, C, D	fibre-reinforced cementitious composites
23	[39]	PET	beverage containers, soft drink bottles	D	admixture to concrete
24	[28]	rubber	tyres	A, B, C	admixture to concrete
25	[37]	PET	bottles	B, C	cement mortar and concrete
26	[47]	PE, PET	bottles, unspecified	A, B, C, D	admixture to concrete, concrete blocks
27	[35]	virgin plastic, LDPE, HDPE, PET, PP, PC, PVC, PS, ABS	electric and electronic equipment, automobile residues, packaging, unspecified	A, B, C, D	admixture to concrete
28	[57]	rubber, PET	plastic bags, bottles, unspecified	D	incorporation in self-compacting cementitious mixes (SCM) (mortar and concrete)
29	[58]	PET, rubber	tyres and bottles	A, B	admixture to concrete
30	[59]	PET, rubber	tyres and bottles	A, D	admixture to concrete
31	[60]	rubber	tyres	A, B, C	admixture to cement concrete

Table 5. *Cont.*

Nr	Reference	Polymers Types	Waste Sources	Dimensions	Applications
32	[51]	plastic waste, rubber, e-plastic	tyres and bags and plastic bottles, electronic industry	A, B, C, D	admixture to concrete
33	[21]	PP, HDPE, PET	bottlers, unspecified	D	admixture to concrete

Legend: PE, Polyethylene; HDPE, High-density polyethylene; LDPE, Low-density polyethylene; PET, Polyethylene terephthalate; PP, Polypropylene; PVC, Polyvinyl chloride; PVA, Polyvinyl alcohol; PS, Polystyrene; EPS, Expanded polystyrene; HIPS, High-impact polystyrene; GFRP, Glass fibre reinforced plastic; PUR, Polyurethane; ABS, Acrylonitrile butadiene styrene; PC, Polycarbonate; MM, Melamine; PA, Polyamide; PO, Polyolefins; E-plastic, plastic from electric and electronic wastes; A, Dust (up to 1 mm); B, Flakes (1–10 mm); C, Pellets (10–25 mm); D, Fibres (length of 25–50 mm).

3.3. Stated Properties

The main physical and mechanical properties that characterize concrete and cement mortar with waste plastic and rubber have been identified. Figure 6 summarizes the 25 main properties investigated by the authors analysed.

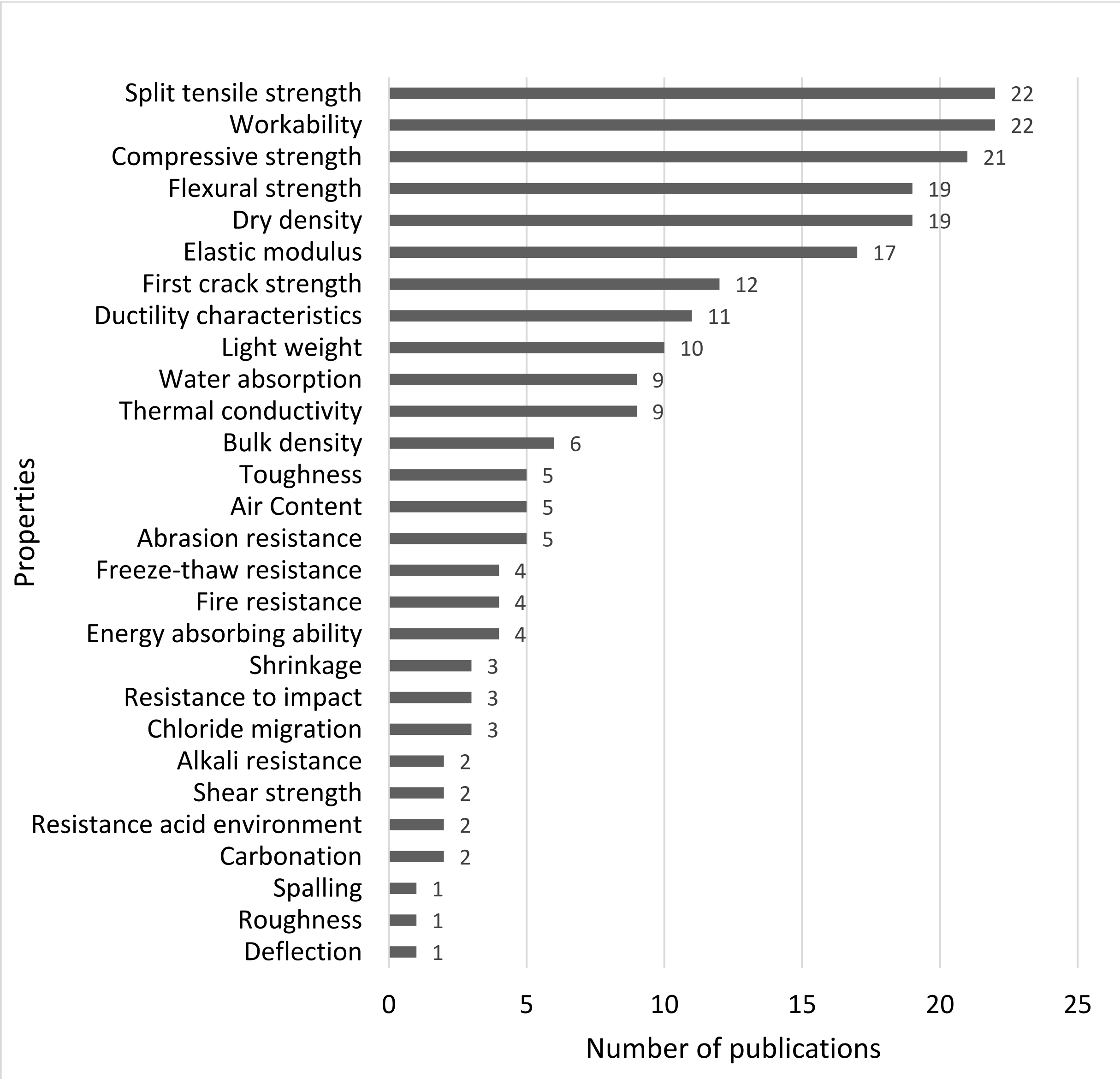


Figure 6. Physical and mechanical properties analysed by authors of the selected reviews.

This representation highlights which are the most investigated properties. Among the physical properties, the workability is the most frequently analysed followed by the dry density, while among the mechanical properties the compressive and split tensile strength are the most frequently investigated (analysed by 21 and 22 authors, respectively), followed by the flexural strength and the elastic modulus (Young's modulus) (18 and 16 articles, respectively). Many others are physical and mechanical properties of less interest to authors, covered in very few studies. Alkali resistance, roughness, spalling and deflection are some examples. Among the reviewed review papers, the paper by Rostami et al. [39] is the article that analyses the largest number of properties (16 shared between physical and mechanical properties), followed by Almeshal et al. [23] and Mercante et al. [36] with 15 properties investigated and, finally, by Novotny et al. [43] with 12 properties. Many other authors have preferred to focus on a few properties, analysing in detail the effect of plastics and rubbers on the characteristics of concrete and cement mortar. In fact, 13 papers analyse fewer than five properties, focusing mainly on compressive and flexural strength and on workability.

It is evident from the literature that most of the studied properties have different results depending on several variables, such as type, size, proportion, and recycling and treatment methods of waste materials used. Some properties, however, seem not to be influenced at all by the cited variables, or influenced only partially, such as fresh and dry densities, which decrease with the increase in plastic and rubber content because the specific gravity of plastic and rubber is significantly lower than that of conventional aggregates or fibres [28,31,35]. Researchers demonstrated that the thermal conductivity always decreases in concrete and cement mortar containing plastic and rubber waste material, leading consequently to better thermal insulation properties than conventional concrete, which can be used to control heat loss from buildings during winter and heat gain during summer [31,37,44,50,56]. The critical issues related to the main properties influenced by the previously cited variables are discussed in the following section.

3.4. Critical Aspects

Among the numerous properties analysed, workability strongly characterizes fresh cement mortar. Workability of concrete is defined as the ease with which concrete can be mixed, transported, placed and finished without segregation and it is measured through slump tests, the K-test and the inverted slump cone test for fibre-reinforced concrete [35]. Research findings show conflicting performances of cement and mortar concrete workability under the influence of polymeric waste aggregates and fibres in the mixture. According to the review conducted by Pacheco-Torgal et al. [56], the workability is mainly dependent on the characteristics and on the treatments of the aggregate, while according to Babafemi et al. [50], it is mainly influenced by the particle shape, size, roughness, water-cement ratio and amount of cement paste. According to the study conducted by Alhasanat et al. [45], the workability increases with the addition of fine recycled plastic aggregates, while it decreases with the addition of fibres and coarse aggregates. Pakravan et al. [5], based on analysis of the reports in the literature related to the influence of PP, PE and PVA fibres, concluded that workability is not very sensitive to the type of fibre.

Among the mechanical properties, the compressive strength presents ambiguous indications among the authors analysed. Compressive strength is the ability of a material to support and resist pressure until it breaks. It is another property described by the authors analysed with conflicting performances in respect to specific characteristics of the composition of cement and mortar concrete. The results available in the bibliography show that the use of alternative materials in the composition of concrete mixes determines a general tendency for the compressive strength of the material to deteriorate, with a marked dependence on the substitution level of fine plastic aggregate (S_{pa}), the shapes (uniform or non-uniform materials), the material used (plastic or rubber) and the water-to-cement ratio (w/c). Almeshal et al. [23] studied the relationship between S_{pa} and compressive strength, highlighting the general inverse relationship between the two aspects. The results presented by Pakravan and Memariyan [14] also confirm that a reduction in compressive strength is observed with the incorporation of PP fibres in concrete at any dosage. The non-uniform behaviour among authors is summarized in the study by Alfahdawi et al. [44], which reports the bibliographic evidence of the effect of plastic ratio substitution on compressive strength in mixes, highlighting the conditions that determine a reduction in compressive strength and those that determine an increase. Gu and Ozbakkaloglu [41], in their review, confirm the general trend towards a progressive reduction in compressive strength, indicating that non-uniformly shaped plastic aggregates decreases more significantly than that of concrete containing uniformly shaped ones. This study also reports that, using plastic fibers with a high ultimate tensile strength, there is a significant improvement in the compressive strength compared to the use of fibres with a low ultimate tensile strength. Novotny et al. [43] emphasize that concrete containing plastic fibres up to 1% have a higher compressive strength, which decreases at 1.5% of plastic fibre content. The ratio of fibre length to fibre diameter is reported as a relevant parameter in defining properties. Using rubber as an alternative material, Mohajerani et al. [42] report a significant reduction in concrete compressive strength with an increase in rubber content. This behaviour is also confirmed by the studies analysed by Roychand et al. [28], who also identified an author who showed a contradictory result.

Linked with the compressive strength, often the split tensile strength and flexural tensile strength are also used by authors for determining strength. Compressive and tensile strength are closely linked, and display similar behaviour [36]. Jandiyal et al. [38] state that split and flexural tensile strength improved with an increase in fibre content, in particular up to a replacement level of 0.1%. With long fibres, flexural strength is greater than using smaller ones. In the same study, bibliographic cases are reported in which these properties have an opposite trend. Also, Novotny et al. [43] confirm these results. Pacheco-Torgal et al. [56] correlate these performances with the characteristics and the treatments of the aggregate.

For the elastic modulus, many studies have not reported significant variations when alternative materials are used [55], although disagreements are attributed to different aspects, such as the type, the shape, the dosage, the w/c ratio and the porosity [36,41,46]

Water absorption is one of the physical properties that present performances that are still much discussed among the authors in the literature, with aspects and situations still being studied in depth. Almeshal et al. [23] report that water absorption increases when the replacement ratio of sand with plastic also increases. This is due to the increase in the porosity of the cementitious matrix. In fact, the increase in water absorption is influenced by the increase in the size of plastic/rubber particles, the content of aggregate and fibres, and the w/c ratio. In analysing the collected papers, the authors also identified divergent experiences, where the water absorption decreases. For Jandiyal et al. [38], this property decreased up to 1% of the fibre content. Increasing behaviour is also confirmed by Rostami et al. [39]. The effect of the shape of the materials was analysed in the paper by Li et al. [31], where it is described that lamellar and angulated plastic aggregates cause higher water absorption in concrete than the corresponding spherical and regular ones. This study also analysed the effect of rubber, which shows a general tendency to have a negative impact on the water absorption of concrete by increasing the content of rubber. Also, for this material, threshold values are highlighted, below which the water absorption tends to decrease, and then increase after exceeding a specific content.

3.5. Open Issues

3.5.1. Environmental Performances

Studies are available on the environmental performances of plastic recycling techniques, reporting that mechanical recycling (e.g., melting and grinding) provides a higher net positive environmental impact than recovery of energy (incineration) or landfilling [37,47]. For example, Jandiyal et al. [38] report that recycling one pound of PET reduces energy use and greenhouse gas emission by 84% and 71%, respectively. It is important to underline that the construction industry (with traditional materials) puts a lot of pressure on the environment, in terms of both the use of resources and the production of waste [48]. However, according to the reviewed literature, no reports are available on environmental analyses, such as life cycle assessment (LCA) based on material flow analysis of plastic waste concrete. Several authors highlight the need to conduct environmental evaluations related to plastic waste concrete [31,37,42] considering the whole life cycle of the final product, such as long-term environmental exposure [9] or waste treatment techniques [57]. Some mechanical properties and performances, such as the workability, of rubber and plastic concrete are influenced by the fact that wastes were previously submitted to a treatment [28]. Pacheco-Torgal et al. [56] highlight the need to study whether these treatments have an environmental impact that shadows the ecological benefits of using rubber and plastic wastes. Comparisons have been made between recycled plastic and steel fibres, considering only the production phase, showing that plastic fibres offer significant environmental benefits over traditional steel reinforcements, reducing carbon dioxide emissions during the production and the extraction of raw materials [21].

3.5.2. Cost Savings and Impacts on the Supply Chain

Practical applications of polymeric waste in concrete and cement mortar involve economic issues. Many authors declare that the use of plastic and rubber waste reduces the cost of the final products compared to the use of conventional raw materials [53]. According to Pakravan et al. [5] and to the studies reviewed by Yin et al. [21], plastic fibres have a significantly low cost compared to steel mainly for two reasons: (i) they need a lower quantity of plastic fibre to achieve the same degree of reinforcement in a concrete footpath of same area; (ii) they require less labour time and expense to prepare the plastic fibres that can be directly mixed with concrete, eliminating the need for preparation of steel. However, no studies are available on detailed economic analyses of plastic or rubber waste-based concrete and cement mortar, to the best of the analysed authors' knowledge. Liew et al. [9] describe some quantitative information on possible economic savings, but without going into too many details. Moreover, Saikia and De Brito [37] suggest conducting a life cycle cost (LCC) analysis in order to investigate cost issues related not only to the production of cement composites containing various types of plastic waste such as aggregate, filler or fibres containing plastic waste aggregates, but also cost implications related to the recycling of the new products at the end of the service life. Other authors, meanwhile, identify a potential cost increase, especially during the manufacturing processes. [28] state in their review that the cost of processing and shredding scrap tyres involves labour, power and equipment, and that the smaller the particle size, the higher the cost associated with its production.

3.5.3. Long-Term Health Implications

A key aspect to be addressed when evaluating the possible degree of pollution related to plastic waste construction products is the potential leaching of toxic constituents from plastic waste construction products [61]. In fact, as demonstrated by several authors, the majority of the plastics contain toxic organic and inorganic chemical constituents such as lead, cadmium, chromium, mercury, bromine, tin, antimony, bisphenol A and chloro-ethane monomer [62–65]. In regard to the use of such materials in cement and mortar concrete, only in [37] authors underline the need to consider the long-term health implications, highlighting a study that reports that the formation of some organic compounds after prolonged curing of PET fibre in simulated cement pore fluid could initiate the alkaline hydrolysis of PET. Also in [28] they conclude their review on the mechanical properties of waste tyre rubber concrete by pointing out that some concerns still need to be investigated, such as the high flammability and resultant release of noxious gases from rubber particles when exposed to fire.

3.5.4. Influence of Recycling Techniques and Treatment Methods

From the analysis of the selected review, it emerges that recycling techniques and treatment methods have an influence on: (i) the properties of the final products; (ii) the environmental performances; (iii) the cost savings. Siddique et al. [35] investigated the main different plastic recycling techniques, namely mechanical recycling, chemical modification and thermal reprocessing, concluding that: (i) mechanical recycling leads to high-quality recycled materials; (ii) feedstock recycling has a greater flexibility in terms of composition and is more tolerant to impurities than mechanical recycling, although it is capital-intensive and requires very large quantities of used plastic for reprocessing to be economically viable; (iii) thermal reprocessing can be applied only to some types of plastics: for example, it could not be applied to thermosets (such as cross-linked polyesters) because they cannot soften at high temperatures without degrading. Moreover, thermal reprocessing cannot be repeated indefinitely since repeated processes may eventually adversely affect the plastic properties. Roychand et al. [28] explored the effect of 20 different rubber treatment methods on the mechanical properties of rubber concrete, demonstrating that treatment methods, such as water washing, water soaking and precoating of rubber with cement paste, could influence the workability, the modulus of elasticity and the abrasion resistance.

4. Conclusions and Prospects for Development

Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted. This tertiary systematic literature review presents the results of studies concerning the potential addition of polymeric waste materials, such as plastic and rubber, to concrete and cement mortar. The use of these wastes is a widespread practice to replace natural aggregates, promoting the development of circular economy solutions, supporting the transition towards greater economic and environmental sustainability of the construction sector.

The recent and widespread literature available has been critically studied through a descriptive assessment of the available reviews and through a structured overview of the use of plastics and rubber, and their effect on the characteristic properties of concrete and cement mortar, as well as the related critical issues and open issues.

Thirty-one review articles have been analyzed, capitalizing on the results of a large number of papers available in the literature.

The results described allow the following conclusions to be highlighted:

- The addition of polymeric wastes in concrete and cement mortar is a viable way to reduce the amount of landfilled and incinerated waste and to reduce the extraction of raw materials.
- Waste polymeric materials can improve some physical and mechanical properties of fresh and hardened composites.
- The physical and mechanical properties of polymeric waste concrete and cement mortar are strictly dependent on several parameters, such as the type, size, shape, amount and treatment of the waste polymeric materials.

The following recommendations for further research proposals are also suggested:

- Environment life cycle assessments should be conducted to evaluate the feasibility of the use of polymeric wastes as an eco-friendly substitute for conventional materials considering all the life cycle stages, particularly the treatment of waste materials and the end of life.
- Economic evaluations should always be conducted when waste material needs treatment before being added to a new product.
- Health and risk implications of polymeric waste concrete and cement mortar should be evaluated during the application and in particular conditions, such as toxic emissions in use or under high temperatures as in the case of fire.

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