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Effect of thermoplastic waste from production on the strength of cement mortars

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Abstract

This paper presents study results on the effect of the addition of polymeric waste on selected mechanical properties (flexural and compressive strength) of cementitious composites with a special emphasis on cement mortars. This research focuses on cement mortars, commonly used in construction applications such as seaports and quays. Here, post-production waste from the production of automobile floor mats is ground to a fraction of 0–2 mm and used in the amounts of 5%, 7.5%, and 10% by weight of cement as an additive or substitute for sand. All the presented tests are conducted in accordance with PN-EN 197-1. The purpose of these tests is to determine the possibility of using thermoplastic waste as an aggregate substitute or additive in cement mortars. The conducted research confirmed the possibility of using the mentioned waste in cement mortar production technology in the amount of 5% as a substitute for sand.

Introduction

The extremely rapid development of science, technology, and industry in the 20th and early 21st centuries has not only positively influenced the improvement of manufacturing methods, the improvement of human living and working conditions, and the quality of products but has also caused a number of threats to the environment (Gucma, Deja & Szymonowicz, 2023). One of the main problems facing modern societies is the systematic increase in the various types of waste produced (Deja, Ulewicz & Kyrychenko, 2021). Currently, there are a large number of polymeric wastes on the market, which continue to be deposited in landfills. Recycling of waste polymeric materials characterized by a diversity of chemical structures and compositions (besides polymer, these materials contain softening agents, UV stabilizers, antioxidants, and coloring agents) has a number of technical and technological limitations (Ulewicz & Siwka, 2010). Therefore, post-production polymeric waste, as well as heterogeneous post-consumer polymeric waste that is coded 16 01 19 (i.e., waste not included in other groups of plastics – used or unusable vehicles, waste from dismantling, or inspection and maintenance of vehicles) continues to be deposited in landfills (Directive 2014/955/EU). Influenced by press reports, which are supported by studies by scientists and specialists about the degradation of the planet and irreversible negative changes occurring in its atmosphere and surface, there is a special emphasis on the use of environmentally friendly solutions in industry, including the construction sector.

In recent years, many research centers have investigated the possibility of using various materials, including waste materials, to create cement composites. These activities are aimed at effectively reducing the consumption of energy and mineral resources. Cement composite production technology uses recyclates that are formed from various waste materials: sanitary and household ceramics (Halicka, Ogrodnik & Zegardlo, 2013; Ulewicz & Halbiniak, 2016), furnace slags and ashes (Popławski, 2020; Jura & Ulewicz, 2021; Kalak et al., 2023), and cathode ray tube (CRT) glass (Walczak et al., 2015; Dębska, Krasoń & Lichołai, 2020), as well as various types of polymer waste (Pietrzak 2018; 2022; Helbrych, 2022). There have also been several reports on the use of recycled rubber waste for concrete production (Koltuńczyk & Nowicka, 2007; Sofi, 2018). With an increase in the content of waste rubber, used as a substitute for sand, concrete mixtures have been characterized by lower (Albano et al., 2005; Gesoglu & Güneyisi, 2007) or higher (Sofi, 2018) workability. Concretes containing the addition of rubber recyclate showed lower values of mechanical parament compared to concretes produced without the waste additive (Madandoust, Ranjbar & Mousavi, 2011; Xu et al., 2012).

In contrast, Blessen, Limbachiya and Kew (Blessen, Limbachiya & Kew, 2016) studied the high-strength properties of concrete containing recycled rubber obtained from post-consumer tires. Rubber crumb was used to replace natural fine aggregate in amounts ranging from 0% to 20% in multiples of 2.5%. The authors of this work observed a significant improvement in the concrete's abrasion resistance and water absorption, while the mechanical properties of the rubber-modified concrete were lower than those of the control concrete. Based on other studies (Skawińska & Foszcz, 2019; Ołdakowska, 2012a, 2012b, 2015), a comparable trend of the effect of rubber waste on the behavior of cement matrices or concretes used in construction can be concluded. The use of rubber waste resulted in a reduction in the compressive strength of the materials tested. The reduction in compressive strength of the tested materials was larger the more rubber waste was employed. The addition of rubber waste resulted in a material with higher deformability and, as a result, reduced stiffness compared to the control samples. Lowering the stiffness also made it possible to obtain a higher fatigue life for the material in which the rubber waste was used and, as indicated by Oldakowska (Oldakowska, 2012b), to change the failure mechanics of the material.

The author's research in earlier works (Ulewicz & Pietrzak, 2021; 2023), in which this type of waste was used in concrete production technology, encouraged this research to be extended to other construction materials. In the cited works, it was shown that the addition of waste thermoplastic elastomer from the production process of automotive floor mats in the amount of 2.5% by weight of cement to concrete (as a substitute for aggregate) did not reduce the mechanical properties of the concrete. The addition of waste in this amount does not reduce the parameters of concrete (i.e., the compressive strength, flexural strength, tensile strength by splitting, frost resistance, and abrasion resistance) with respect to materials produced without the addition of waste thermoplastic elastomer. Concrete modified with waste thermoplastic, obtained from used car mats or post-production waste, can be used for elements protected from direct exposure to the weather (e.g., industrial floors and ceramic tile floors).

Car mats are usually made of needle velour (polypropylene or polyamide) finished with rubber abrasion (e.g., polybutadiene and polyolefins). Also available are carpets based on poly(ethylene terephthalate), the so-called PET, and polyethylene-polypropylene copolymer (Komornicki et al., 2013). The liners also contain a flame retardant, mineral fillers, and dyes. Post-production waste with a known composition to the manufacturer can be returned to the production process (material recirculation) or be used to manufacture other products. However, in practice, it is often deposited in landfills. Therefore, the search for new opportunities in the use of post-production waste generated in the production of automobile floor mats is an important issue for the sake of environmental protection and reducing the consumption of raw materials.

Research materials and methodology

Materials

Portland cement CEM I 42.5R, norm sand, tap water from an intake in Czestochowa, and post-production waste of thermoplastic elastomers, generated in the production of automobile floor mats from a manufacturing plant located in the Silesian province, were used for the cement mortar tests. After initial manual grinding, the post-production waste (Figure 1) was ground to a 0–2 mm fraction in a granulator (SG-2417 SHINI). Using a WDXRF X-ray spectrometer (Model S8 Tiger from Bruker Company), the elemental composition of the thermoplastic elastomer waste used in the study was determined; this is shown in Table 1.

A TG thermal analysis was also performed for the waste used in this study. The test was carried out in a Jupiter STA 449 F5 thermoanalyzer (from Netzsch) in the range from 30 ºC to 600 ºC with

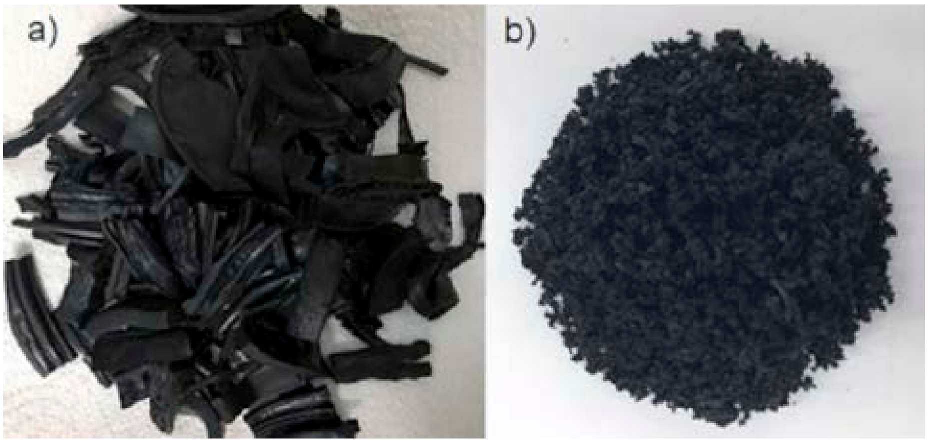

Figure 1. Post-production waste from automotive carpet production: (a) pre-shredded material and (b) shredded to a 0–2 mm fraction

Table 1. Percentage of elements in post-production waste

Chemical composition [% by mass]										
Ca	Si	Al	S	Zn	Fe	Mg	Ti	K	C	Other
2.20	0.49	0.28	0.28	0.51	0.02	0.10	0.02	0.03	81.51	14.56

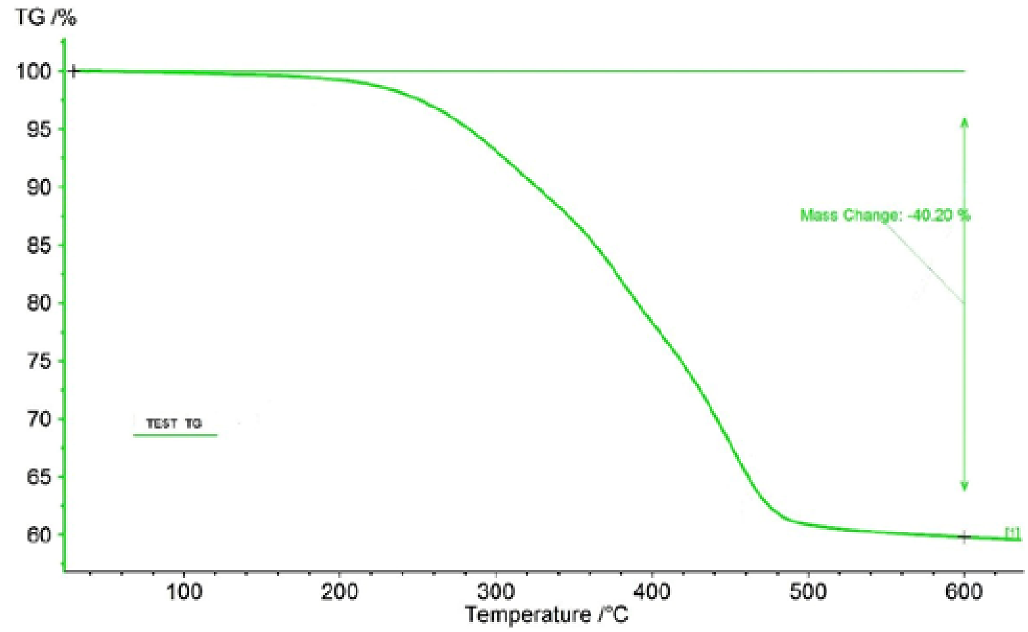

Figure 2. TG thermogram of post-production thermoplastic elastomer (EPDM)

a temperature rise rate of 10 ºC/min in an air atmosphere, with a gas flow rate of 100 cm^3/min. A loss of weight of the samples can be seen in a wide range of temperatures from ca. 200 °C to 500 °C and is ca. 11% (Figure 2). The processes connected with weight loss are endothermic.

Methodology

Flexural and compressive strength tests of cement mortars were carried out for 40×40×160 mm barrels. The series of control beams (ZK) was made as a standard mortar based on Portland cement CEM I 42.5R from CEMEX. Based on this cement, six series of cement mortars modified with the post-production waste from the production of car liner (W) were also made, using the waste in the amounts of 5%, 7.5%, and 10% by weight of cement as an additive and as a substitute for sand in the amounts of 5%, 7.5%, and 10% by weight of cement by introducing a volumetric correction of sand (Table 2).

Table 2. Components of standard mortar and mortars with waste

Series of mortars	Components [g]			
	cement	water	aggregates	waste
ZK	450	225	1350	–
Z1	450	225	1350	22.5
Z2	450	225	1350	33.75
Z3	450	225	1350	45.0
Z4	450	225	1290	22.5
Z5	450	225	1278	33.75
Z6	450	225	1254	45.0

Research results and discussion

Flexural and compressive strength tests were carried out on the prepared series of mortars after 2, 7, and 28 days of maturation (Figure 3). The tested properties of the mortars were determined in accordance with PN-EN 197-1 on a Toni Technik-type 2030 testing machine.

The flexural strength tested after two days of maturation for the control barrel series (ZK) was 3.7 ± 0.38 MPa, while that of the waste-containing barrel series (Z1–Z6) was lower, ranging from 2.8 ± 0.21 MPa – 3.3 ± 0.15 MPa (Table 3). After seven days of maturation, a decrease in the average flexural strength compared to the control series (i.e., a 14.7% – 42.6% decrease) was noted for all the Z1–Z2 barrel series. On the other hand, the average flexural strength tested after 28 days of maturation for all the series of barrels containing waste was lower than the average flexural strength of the control series (8.5 ± 0.23 MPa). The lowest decrease (8.1%) was recorded for the Z4 series, in which 5% of waste was used as a substitute for sand. On the other hand, the largest saucer of the studied parameter was recorded for the Z3 series, whereas 10% of waste was shod as an additive.

Table 3. Results of the bending and compressive strength test for cement mortars of the series

Series of cement mortars	Bending strength, [MPa]			Compressive strength, [MPa]		
	after 2 days	after 7 days	after 28 days	after 2 days	after 7 days	after 28 days
ZK	3.7	6.8	8.8	22.3	35.0	47.0
Z1	3.3	5.8	7.7	19.2	29.5	40.5
Z2	3.2	4.6	7.5	16.3	25.0	38.6
Z3	3.3	4.1	6.4	14.3	23.5	34.0
Z4	2.8	4.8	7.8	20.5	28.8	43.2
Z5	3.1	4.2	7.4	18.8	26.3	39.4
Z6	3.3	3.9	6.7	15.6	24.5	36.8

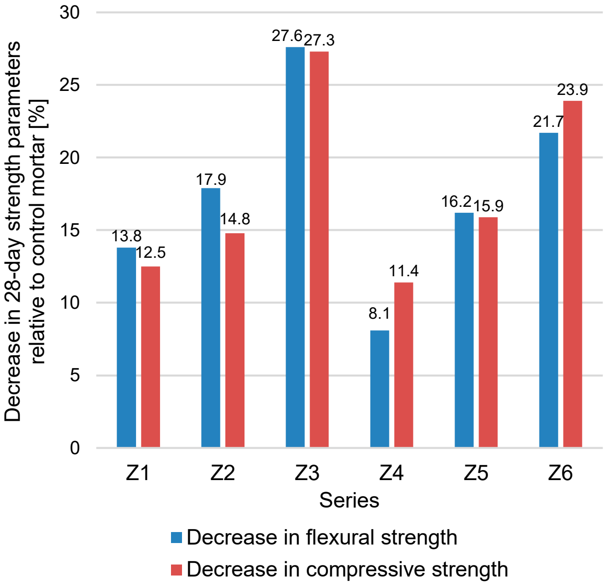

Figure 4. Percentage decrease in average compressive/bending strength of the cement mortars in each series compared to the control series (ZK)

Figure 3. Strength tests of cement mortar beams

According to the standard (PN-EN 197-1), the average compressive strength tested after two days for cement of class 42.5R should be greater than 20 MPa. These requirements were only met for the series of control beams and for the Z4 series, to which a waste material of 5% by weight of cement was added as a substitute for the sand. However, for the other series of beams made with the addition of waste material, the average compressive strength ranged from 14.3 ± 0.44 MPa to 19.5 ± 0.08 MPa. Compressive strength values tested after seven days were also lower (15.5% – 32.8%) for all the series of Z1–Z6 series beams compared to the control series (Figure 4). The average 28-day compressive strength of the control beams was 47.0 ± 0.54 MPa. Figure 5 shows a comparison of earlier proprietary tests for the 28-day compressive strength of the cement mortars, in which thermoplastic post-consumer waste from used, stored car mats was used (Pietrzak & Ulewicz, 2018).

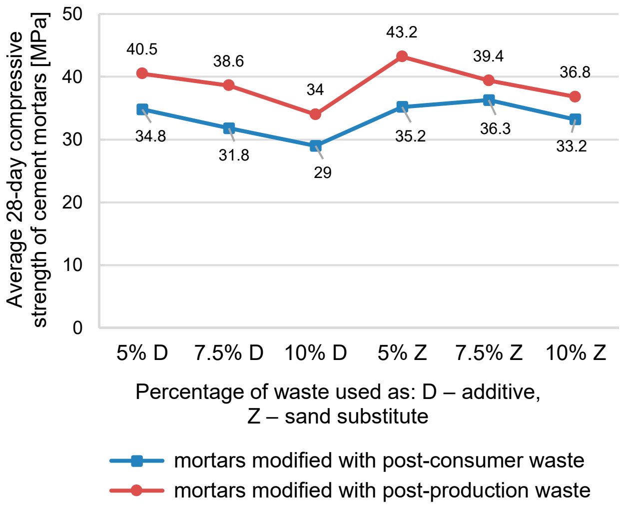

Figure 5. Average compressive strength of cement mortars modified with post-consumer and post-production waste of the thermoplastic elastomers (values regarding post-production waste from Pietrzak & Ulewicz, 2018)

The tests carried out for the cement mortars modified with post-consumer waste did not confirm the possibility of using waste as a substitute for fine aggregate, i.e., sand, or as an additive to cement mortars. None of the modified series of cement mortars met the strength requirements for cement mortars tested after 28 days of maturation since they did not achieve an average compressive strength higher than 42.5 MPa. However, in the case of the use of post-production waste, more favorable strength parameters for the cement mortars were obtained. In the case of using 5% of the waste as a substitute for fine aggregate, the strength requirements for cement mortars tested after 28 days of maturation were met since, for cement CEM I 42.5R, the average compressive strength was above 42.5 MPa.

Similar observations regarding the effect of using rubber granules in cement mortar technology were found by Ganijan et al. They used rubber granules from shredded tires as a replacement for cement. These researchers found that the compressive strength of the cement mortars depends primarily on the size of the rubber granules and their amount. Replacing cement with 5% rubber granules did not contribute to a significant reduction in compressive strength (about a 5% drop). However, further increasing the amount of granules to 7.5% and 10% resulted in a decrease in compressive strength after 28 days by 20% and 40%, respectively. The authors of another paper (Skowinska & Foszcz, 2019), using rubber granules (1–4 mm fraction) for the cement mortars at 5%, obtained a decrease in strength of about 20%. On the other hand, replacing cement with 15% rubber waste contributes to a strength reduction of nearly 50%. The researchers also indicated that the grain size of the rubber

Table 4. Use of waste polymers/elastomers in cement mortar

Sequence number	Waste dosing	Size of the waste grains	Compressive strength				Compressive strength	Reference
			after 7 days	after 14 days	after 28 days	after 56 days		
1	6%	300–600 μm	–	–	↑	–	–	Chou et al., 2010
2	10 g, 20 g, 30 g	0–5 mm	–	–	↑ ↔	–	–	Jura & Ulewicz, 2016
3	5%, 15%	1–4 mm	–	–	↓	–	–	Skowińska & Foszcz, 2019
4	5%	–	↓	↓	↓	↓	–	Chen & Lee, 2019
5	–	–	–	–	↓	–	–	Korentz & Szmatuła, 2020
6	25%, 32%, 40% mas.	0–2 mm 2–4 mm	–	–	↑ ↓	–	↑	Petrella & Notarnicola, 2021

Signage ↑, ↓, ↔ signify increase, decrease, and same level of tested strength parameter in relation to the control test.

waste used does not significantly affect the strength of the mortars tested. Similarly, when using different types of cement, the authors did not observe that any of them obtained smaller or larger decreases in strength with the addition of rubber waste. Microstructure studies carried out for mortars with the addition of rubber waste indicated that the hydration process proceeds appropriately.

Table 4 presents a summary of scientific reports related to the use of waste rubber in cement mortar with a focus on compressive strength.

Conclusions

Numerous researchers have attempted to determine the feasibility of using various types of waste, including biomass combustion dust, ceramics, glass cullet, and some synthetic plastics, for the manufacture of concrete as well as cement mortar. In the case of plastics, according to a literature review, due to their diverse physicochemical properties (with varying compositions of modifying additives and diverse chemical structures of the main polymer), their use is particularly difficult and requires research separate for a select group of plastics each time. Production of polymer composites is more expensive than ordinary concrete, which is primarily due to the cost of the polymer resins used. A very important issue, therefore, is the possibility of using polymer waste (mainly plastic waste) to modify concretes and mortars. The ever-increasing amounts of this type of waste cause both environmental and economic problems, which are related to the poor biodegradation of plastics. Tests conducted for the designed cement mortars confirmed the possibility of using post-production waste generated in the production of car liners as a substitute for fine aggregate, i.e., sand in the amount of 5%. Only this modified series of cement mortars met the strength requirements for cement mortars tested after 28 days of maturation. This is because it achieved the average compressive strength of above 42.5 MPa for the CEM I 42.5R cement. The use of post-production waste thermoplastic elastomers in cement composite technology aligns with the concept of sustainable development, including sustainable construction.

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