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Cement Mortars Based on Polyamide Waste Modified with Fly Ash from Biomass Combustion—A New Material for Sustainable Construction

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Abstract: The article presents an analysis of the possibility of using the waste of polyamide 6 modified with fly ash (in the amount of 5, 10 and 15%) from the burning of wood–palm kernel shells biomass as an addition to cement mortar. Fly ash from the burning of biomass in a circulating fluidized bed boiler (which currently has no practical use) was first used to produce polyamide 6, and then post-production polymer waste (added at 20, 40 and 60%) was used to produce ecological mortar. The use of this type of waste is both economically profitable and desirable due to the need to implement waste material management processes in a closed circuit. The addition of polyamide 6 waste containing 5% fly ash in amounts of 20 and 40% and waste containing 10% ash in 20% to cement mortars improves their mechanical properties. The compressive strength of cement mortars (after 28 days of maturation) containing 20 and 40% of polyamide waste containing 5% fly ash increases by 6.6 and 4.6%, respectively, and the flexural strength by 4.9 and 3.4% compared to the control mortars. However, the compressive strength of mortars with the addition of 20% polyamide waste containing 10% fly ash increases by 4.2% and the flexural strength by 3.7%. Cement mortars modified with waste are characterized by slightly lower water absorption and mechanical strength after the freezing–thawing process (frost resistance) compared to control mortars and do not have an adverse effect on the environment in terms of leaching metal ions.

Keywords: cement mortar; fly ash; polyamide waste; circular economy; sustainable construction

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Citation: Ulewicz, M.; Jura, J.; Gnatowski, A. Cement Mortars Based on Polyamide Waste Modified with Fly Ash from Biomass Combustion—A New Material for Sustainable Construction. *Sustainability* **2024**, *16*, 3079. https://doi.org/10.3390/su16073079

Academic Editor: Manuela Almeida

Received: 11 March 2024
Revised: 2 April 2024
Accepted: 5 April 2024
Published: 8 April 2024

1. Introduction

For several years, there has been an increase in the amount of biomass burned by power plants and thermal-electric power stations, and, consequently, an increase in the amount of fly ash produced. Every year, approximately 900–1000 million tons of waste are generated from the energy sector in the world, of which approximately 100 million tons are generated in the European Union (EU) countries [1]. It is estimated that approximately 476 million tons of fly ash are produced annually from the biomass burning process [2]. Unfortunately, the fly ash generated from the burning of biomass itself is a waste that is particularly difficult to manage due to the very high variability of its chemical composition determined by the type of biomass burned and its burning technology [3]. This waste may also contain toxic compounds harmful to the environment, such as heavy metal ions, polycyclic aromatic hydrocarbons or volatile organic compounds. An overview of the developed technologies for processing waste from the burning of various types of biomasses (wood, agricultural, food waste, sewage sludge) is presented in [4], where a number of solutions and problems in the application of their potential applications are indicated. However, in practice, fly ashes generated in power plants and thermal-electric power stations from the process of combustion of biomass in fluidized bed boilers, classified in group 10 01 82 (Decision

2000/532/EC), are currently deposited in waste landfills, usually on-site [5], because there is not an economically effective and ecological management technology developed for them. Considering the policies of various companies for sustainable development, taking into consideration an integrated view of costs, quality and safety of the product at all stages of its life cycle [6,7], also in the case of this waste, every effort should be made to develop technologies that allow for the effective management of this waste ash.

In the literature [8,9] there is a proposal to use fly ash from biomass combustion due to its valuable ingredients (i.e., calcium, magnesium, potassium and microelements) to fertilize plants and improve soil properties. Unfortunately, the proposed direction of using fly ash in agriculture and for the re-cultivation of degraded land, due to the large amounts of waste generated annually, will not solve the problem of their effective management. Other directions of research are necessary, aiming to develop effective technologies for using the ever-growing amount of fly ash from fluidized beds. Attempts have been made to use waste fly ash for the synthesis of zeolites [10–13], the production of plastics [14,15], geopolymers [16,17], as well as construction materials [18–29]. The search for new solutions is particularly important as it is estimated that the global biomass electricity market will grow at a compound annual growth rate (CAGR) of 5.73% in 2023–2032 [30] and, consequently, the amount of waste ash will increase.

The functioning of a circular economy should contribute to both a decrease in energy consumption and CO_2 emissions, as well as a reduction in the consumption of natural resources. The construction sector consumes most of the natural resources. It uses approximately 50% of all extracted raw materials [31,32], and also generates large amounts of waste. Therefore, the "Sustainable Development Goals (SDG)" published by the United Nations in 2015 indicate construction as a strategic area in which actions should be implemented in the field of sustainable production and consumption, improving the efficient use of natural resources and reducing waste generation [33]. In relation to these goals, the potential implementation of the production of construction materials in which natural raw materials are replaced with waste is an important direction of action. However, despite many research works [18,20,22], the influence of fly ash from biomass burning on the physical and mechanical properties of cement composites produced with their use has not been clearly determined. Reports show that they can both cause an increase [34,35] and a decrease [36,37] in the mechanical properties of cement-based composites manufactured with their participation. Moreover, whenever materials containing dangerous compounds (e.g., heavy metals, aromatic hydrocarbons) are incorporated into the composite, there is a concern whether they will be washed into the environment during a long period of exploitation in changing climatic conditions.

Taking into account the above-mentioned potential threat and the assumptions of a circular economy, we assumed that fly ash from the burning of biomass itself can be used to modify the properties of polyamide 6, and waste of this modified polymer material can be used to produce ecological cement-based composites such as cement mortars or concrete. The first stage, i.e., the synthesis of modified polyamide 6, was described by us in the work [38]. The polymer composites produced with fly ash from the burning of wood–palm kernel shells biomass (added in amounts of 5, 10 and 15% as a filler) are characterized by better thermomechanical properties compared to polyamide 6 (PA6) without a filler. Moreover, composites modified with the addition of 5% fly ash are characterized by greater durability of the elastic modulus, mainly in the temperature range from (-100) to 80 °C. Modification of polyamide 6 with fly ash improved its thermomechanical and functional properties, which allows for wider use of the obtained materials. Then, in the second stage of the research presented in this work, the modified polymer waste was used to produce cement-based composites. In the literature, one can find many reports on the use of various polymer materials for this purpose [39], although there are critical words [40,41] regarding such use. The literature review shows that polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS) and rubber waste [19,41–43] were most often used to produce cement mortars and concretes. There are significantly fewer reports on the use of other polymer materials, including polyamide, although this material was used both as waste and as a clean, synthesized fiber [44–61]. Polyamide waste [44–49] was used both for the production of cement mortars and concretes. Salas et al. [44] showed that replacing sand with waste polyamide powder in the amount of 25 and 50% modifies the properties of fresh and hardened mortar, while maintaining its appropriate properties, such as workable life, water retention, vapor permeability and bonding in mixtures, while the addition of 75 and 100% has a negative impact on the above-mentioned properties. In turn, Yuan et al. [46], showed that the addition of hot-melt polyamide (HMP) in the amount of 1, 3 and 5% improves the workability of the mortar, but leads to a decrease in its compressive strength. The compressive strength of mortars decreased with an increase in the volume percentage of aggregate replacement by polymer, and for mortars containing 5% waste polyamide, it was lower by 19.8% compared to the control sample. At the same time, an increase in flexural strength was observed for mortars containing 1 and 3% waste, in both cases by 10.6% compared to the control mortar, while the addition of 5% waste reduced the flexural strength of mortars by 5.7% compared to the control mortar. Polyamide (in the form of fibers) was much more often used as an additive to concrete. Halvae et al. [50] showed that the use of 6 and 12 mm long PA6 and PA66 fibers improves the compressive and flexural strength of concrete. The strength of concrete containing PA66 fibers was higher by 50% compared to the control concrete, and the flexural strength for concretes reinforced with 6- and 12-mm fibers was higher by 45 and 98%, respectively. Koksal et al. [51] showed slight differences in the strength of concretes after adding polyamide fibers compared to polypropylene fibers. However, Haghi et al. [52] showed that the use of polyamide-66 yarn reduces cracks in lightweight concrete produced with large-sized polystyrene (EPS) balls. In turn, Vianna et al. [53] observed lower strength and faster appearance of cracks (after 5 days) for concretes reinforced with polyamide microfiber in the amount of 0.9 kg/m^3 than for conventional concretes (cracks appeared on the seventh day). Reinforcing concrete with glass fibers in the same amount delayed the time of crack formation (they appeared after eight days). In all microfiber-reinforced concretes, regardless of fiber type, a significant reduction in crack width was observed. The influence of the addition of 0.25, 0.5 and 0.75% of micro- and macro-polyamide (PA) fibers on the workability, compressive strength, splitting, tensile and flexural strength, as well as the compressive strength of lightweight structural concrete was determined. It has been shown that polyamide fibers with a length of 54 mm and a diameter of 0.55 mm significantly increase the tensile and flexural strength, and slightly increase the compressive strength. Concretes with the addition of 0.75% of these fibers obtained higher tensile, flexural and compressive strengths by 30.2, 35.1 and 7.5%, respectively, compared to the control concrete. The addition of this amount of microfiber with a length of 12 mm and a diameter of 0.075 mm does not affect the compressive strength, but only increases the tensile and flexural strength of the concretes by 22.2 and 26.9%, respectively, in relation to the control samples [54].

In this article, an attempt was made to assess the possibility of using waste polyamide 6 modified with fly ash for the fabrication of cement mortars. This proposed solution is an innovative approach to the management of fly ash waste from the burning of biomass. In the literature on the subject, there is no such comprehensive and innovative solution to the problem of waste management, which currently has no practical application. Considering that the concept of using fluidized bed combustion fly ash to first produce modified polyamide 6 and then use its waste to produce mortars is ecologically desirable, this study also assessed its economic effectiveness. The management of polyamide 6 waste modified with biomass fly ash for the production of ecological composites would significantly reduce the consumption of natural resources necessary for the production of building materials and would also limit the unfavorable impact of fly ash deposited in company landfills on the natural environment.

2. Materials and Methods

2.1. Waste Characteristics

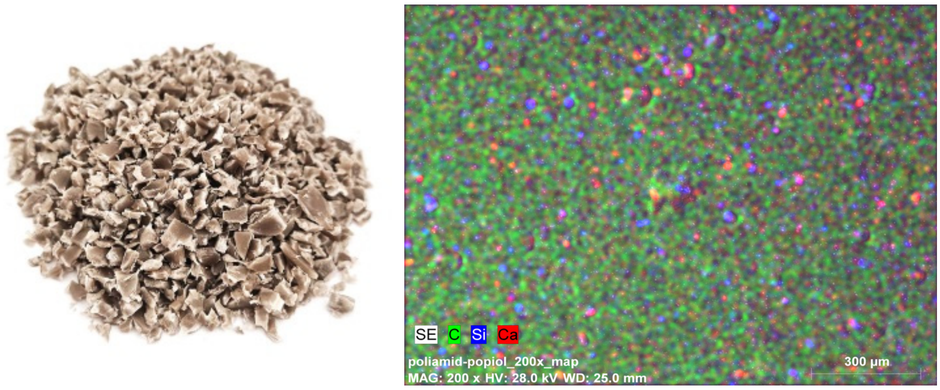
Waste from the polyamide production process using fly ash from the burning of wood—palm kernel shells biomass in a CFB boiler (circulating fluidized bed boiler) was used for the research. Polyamide was modified with the addition of 5, 10 and 15% fly ash. We presented the method of producing this material in the previous article [38]. The properties of polyamide 6 modified with biomass fly ash consisting of 20% palm kernel shells and 80% waste firewood from a power plant located in the Świętokrzyskie Voivodeship (Poland) are presented in Table 1. The chemical composition of biomass fly ash determined per the standard PN EN 450 1:2012 [62] using an X-ray Florescence (XRF; spectrometer Spekom, Thermo Fisher Scientific, Waltham, MA, USA) is presented in Table 2. Figure 1 shows the photos of the used polyamide 6 waste modified with fly ash. Figure 2 shows thermogravimetric curves. Differential scanning calorimetry tests (DSC) were carried out on the DSC 200 PC Phox device (Netzsch Group, Selb, German). Analyzing the obtained thermograms, slight changes in the melting temperature maximum and a decrease in the melting enthalpy value with an increase in fly ash content were found. The addition of 15% fly ash caused a slight shift in the melting point of the crystalline phase towards lower temperatures. Dynamic mechanical analysis tests (DMTA) were performed on a DMA 242 (Netzsch Group, Selb, German) device. The research was carried out under the mode of a 3-point bending clamp with an oscillatory frequency of 1.0 Hz. An increase in the value of the storage modulus was recorded over the entire temperature range of the test for polyamide modified with fly ash. The addition of fly ash resulted in a decrease in the glass transition temperature.

Table 1. Characteristics of polyamide 6 modified with various additions of fly ash determined by DSC and DMTA methods, calculated from the Netzsch Proteus program.

Type of Material	Melt Temp., [°C]	Melting Range of the Crystalline Polymer Phase, [°C]	Enthalpy of Melting [ΔH, J/g]	Glass Transitions Tg, [°C]	Coefficient of Mechanical Loss Tg D [-]
PA	224.5	218.9–229.5	50.93	66.8	0.16
PA + 5% fly ash	223.9	218.8–230.1	52.26	67.1	0.15
PA + 10% fly ash	224.4	220.5–228.6	41.54	64.4	0.13
PA + 15% fly ash	224.1	219.1–227.8	39.05	62.2	0.14

Table 2. Chemical composition of fly ash used for polyamide 6 synthesis.

Oxide/Element	Content, [%]	Oxide/Element	Content, [%]
SiO_2	57.54	MnO	0.51
CaO	17.26	TiO_2	0.30
K_2O	3.93	CuO	0.02
Al_2O_3	4.82	Cr_2O_3	0.01
MgO	2.32	ZnO	0.06
Fe_2O_3	2.94	BaO	0.08
P_2O_5	2.01	SO_3	2.71
PbO	0.02	Cl^-	1.06
Na_2O	0.39	Other	4.02



(**a**) (**b**)

Figure 1. Waste polyamide 6 modified with 15% fly ash (**a**) and a microscope photo at 400× magnification with the dominant elements in this area (**b**).

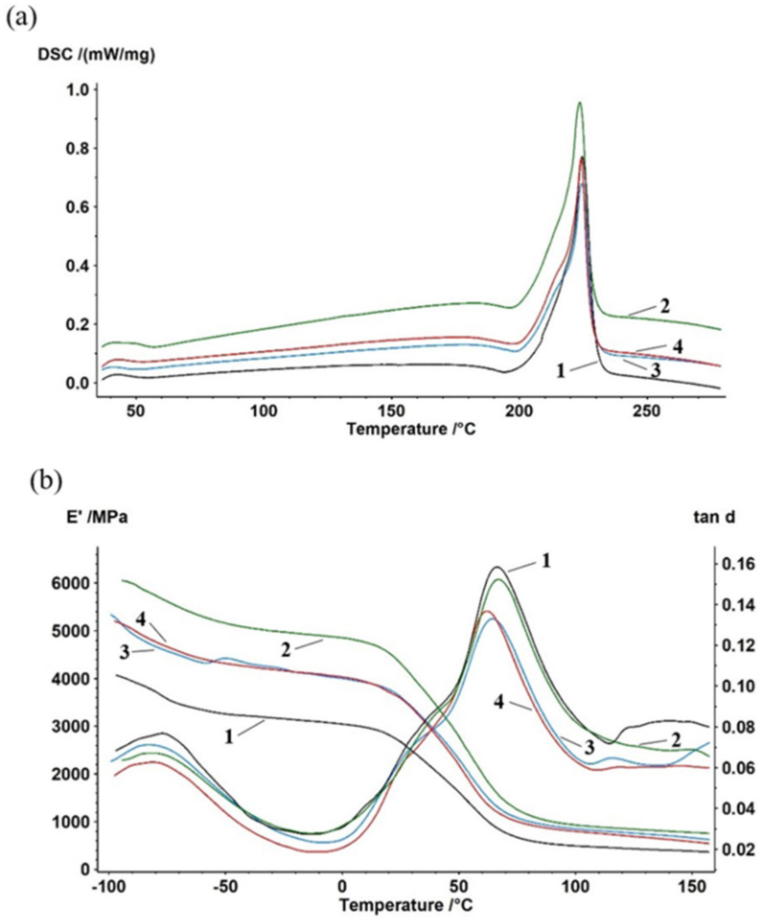


Figure 2. DSC (**a**) and DMTA (**b**) thermograms for fly ash-modified polyamide: 1—PA, 2—A + 5% biomass fly ash, 3—PA + 10% biomass fly ash, 4—PA + 15% biomass fly ash.

2.2. Preparation of Cement Mortars

Cement mortars modified with waste were made using Portland cement CEM I 42.5 R (Cemex, Poland), sand (according to the PN EN 196-1 standard [63]) and water from the Czestochowa intake with a pH of 7.6 and an ion content of Cl^- = 33.5 mg/dm^3 and NO_3^- = 37.6 mg/dm^3. The compositions of the designed cement mortars are presented in Table 3. Polymer waste with a grain size < 2 mm containing 5, 10 and 15% of fluidized bed fly ash was added in the amount of 20, 40 and 60% of the cement mass.

Table 3. The composition of tested series cement mortars.

Series	Cement CEM I, g	Standard Sand, g	Water, cm^3	Polyamide + 5% Fly Ash, g	Polyamide + 10% Fly Ash, g	Polyamide + 15% Fly Ash, g
CS	450	1350	225	-	-	-
5/20	450	1350	225	20	-	-
5/40	450	1350	225	40	-	-
5/60	450	1350	225	60	-	-
10/20	450	1350	225	-	20	-
10/40	450	1350	225	-	40	-
10/60	450	1350	225	-	60	-
15/20	450	1350	225	-	-	20
15/40	450	1350	225	-	-	40
15/60	450	1350	225	-	-	60

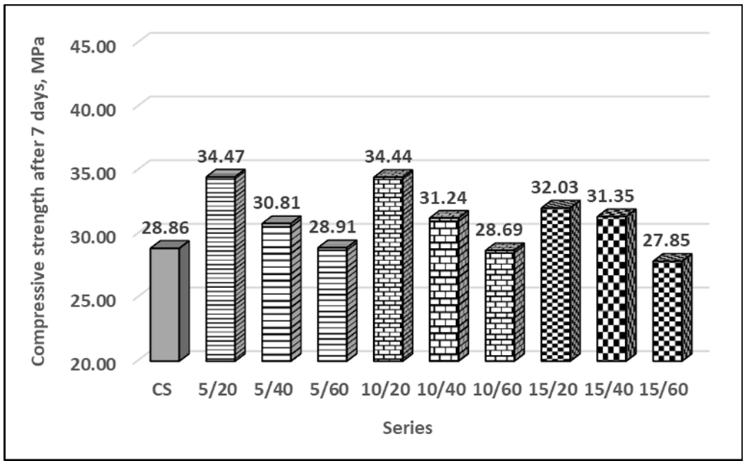
2.3. Research Methods

Cement mortars for testing were made according to the PN-EN 998-2:2016-12 norm [64]. The compressive and flexural strength of the produced mortars was tested on samples 40 × 40 × 160 mm according to the PN EN 1015-11:2020-04 norm [65]. Samples for flexural and compressive strength tests were made on samples taken out of water at a temp. of about 20 °C. The flexural and compressive strength tests were performed using an automatic press for measuring (type MMC-3742 from Multiserw using MMC-0120/E and MMC-0121/E inserts (ToniTechnik 2030, Berlin, Germany)) according to PN-EN 196-1 [63]. The absorption test of the tested cement mortars was carried out according to the PN-85/B-04500 norm [66], and the samples were dried in a POL-EKO dryer, type SLW 240-W STD (ToniTechnik 2030). The frost resistance of concretes was tested based on the PN-85/B-04500 norm [66] using a Toropol chamber (typ K-015 (ToniTechnik 2030)), and samples with sides of 40 × 40 × 160 mm were subjected to 25 freezing and thawing cycles. As part of the research, metal ion leaching analysis was also performed per the PN-EN-12457-2:2006 norm [67].

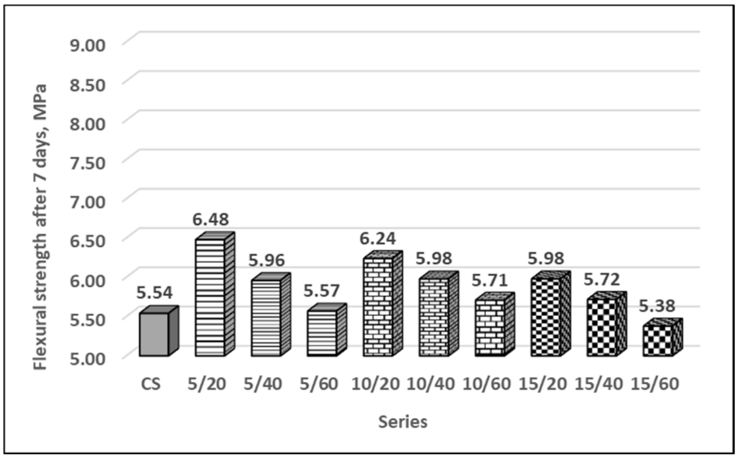
3. Results and Discussion

3.1. Mechanical Strength of Mortars Containing Waste

The prepared cement mortar samples with dimensions of 40 × 40 × 160 mm were subjected to compressive and flexural strength tests after 7 and 28 days. The early compressive strength of the control mortar after 7 days was 28.86 MPa. All series of mortars modified with the addition of 20, 40 and 60% of polyamide comprising 5% of fly ash from biomass burning showed higher compressive strength after 7 days of aging than the series of control mortars without the addition of waste (Figure 3a). Higher early compressive strength was also achieved by the series of mortars modified with the addition of 20 and 40% of polyamide comprising 10% of fly ash from biomass burning, while the addition of 60% of this waste did not significantly affect this parameter. The highest early compressive strength was achieved by mortars containing 20% of polymer waste with 5% fly ash content, which was 19.5% higher than the strength obtained for the control series samples. A similar trend of changes was observed for the early flexural strength of mortars modified with polyamide waste containing both 5% and 15% fly ash. The highest early flexural strength was achieved by mortars containing 20% polymer waste with 5% fly ash content, which was 16.9% higher than the strength obtained for the control series samples (Figure 3b). The decrease in compressive strength of cement mortars after the addition of other polyamide waste was also observed by Salas et al. [44]. With an increase in the amount of added polyamide from the laser sintering process (with a grain size of less than 1 mm and a density of 1070 kg/m^3) in the range from 25 to 100%, they observed a decrease in strength ranging from 13.8 to 61.2% in relation to the control mortars. Also, Yuan et al. [46] observed a decrease in the compressive strength of cement mortars with an increase in the volume of added hot-melt polyamide (HMP). The compressive strength of the mortar after adding 1, 3 and 5% of polyamide was 7.2, 14.2 and 19.8% lower, respectively, than those obtained for the control mortars. However, an increase in the flexural strength of mortars containing 1 and 3% HMP was observed compared to the control mortar, in both cases by 10.6%. The flexural strength of the mortar with the addition of 5% HMP was reduced by 5.7% compared to the control mortar. The addition of various polymer materials (ranging from 5 to 100%), as shown in the review by Babafemi et al. [43], also reduces the mechanical strength of concrete, which is caused by the lack of chemical bonding between cement and the polymer material.



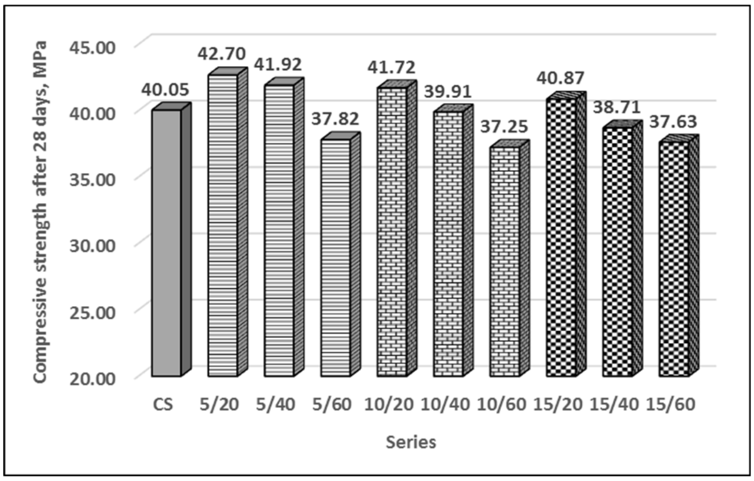
(**a**)



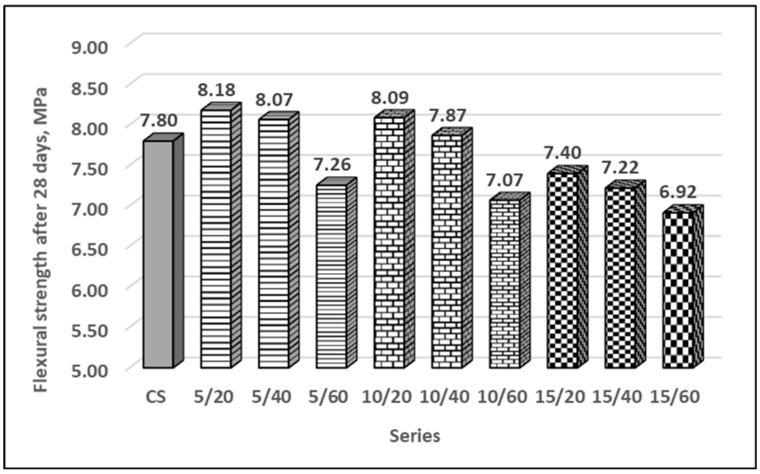
(**b**)

Figure 3. Average compressive (**a**) and flexural (**b**) strength after 7 days of tested cement mortars.

The compressive strength of the control mortar after 28 days was 40.05 MPa. The series of mortars modified with the addition of 20 and 40% of polyamide comprising both 5% and 15% of fly ash from biomass burning showed higher compressive strength than control mortars without the addition of waste (Figure 4a). However, the compressive strength of mortars modified with the addition of 60% ash-modified polyamide (both 5 and 15%) was lower than that of the control mortars. The highest compressive strength after 28 days was achieved by mortars containing 20% polymer waste containing 5% fly ash, which was 6.1% higher than the strength of control samples. However, after 28 days, only mortars modified with 20 and 40% polyamide containing 5% fly ash had higher flexural strength than the control samples, which was higher by 4.9 and 3.4%, respectively. The addition of modified polyamide with 15% ash content reduced the flexural strength of mortars in the range of 5.13 to 11.35% (Figure 4b).



(**a**)



(**b**)

Figure 4. Average compressive (**a**) and flexural (**b**) strength after 28 days of tested cement mortars.

3.2. Water Absorption of Mortars Modified with Waste

Next, the water absorption of the tested cement mortars was determined according to the PN-85/B-04500 norm [66]. The water absorption of the control mortars was 7.74%. Mortars modified with the addition of 20, 40 and 60% of waste polyamide, regardless of the fly ash content, showed lower water absorption than control samples (Figure 5). The difference between the control mortar and the mortar containing 60% polyamide with 5, 10 and 15% fly ash content was 18.51, 10.72 and 10.19%, respectively. The water absorption of mortars and concretes directly exposed to weather conditions should not exceed 5%, and in the case of materials protected from direct weather conditions, 9%. Therefore, concerning these guidelines, both control mortars and waste-modified mortars can be used indoors. Mortars modified with polyamide 6 waste with fly ash are characterized by reduced water adsorption compared to standard cement mortars. Significant differences in water absorption between control mortars and mortars modified with the addition of polyamide were observed by Yuan et al. [46]. It has been shown that the water adsorption of mortars with the addition of hot-melt polyamide (HMP) increases rapidly within 6 h and stabilizes after 24 h. After 24 h, the water penetration depth of mortars containing 1, 3 and 5% HMP increases by 4.55, 24.55 and 45.45%, respectively, compared to the control mortar [46]. However, the addition of rubber (from 5 to 70%), as reported in the review by Rashad et al. [19] may cause both a decrease and an increase in water absorption of both mortars and concretes.

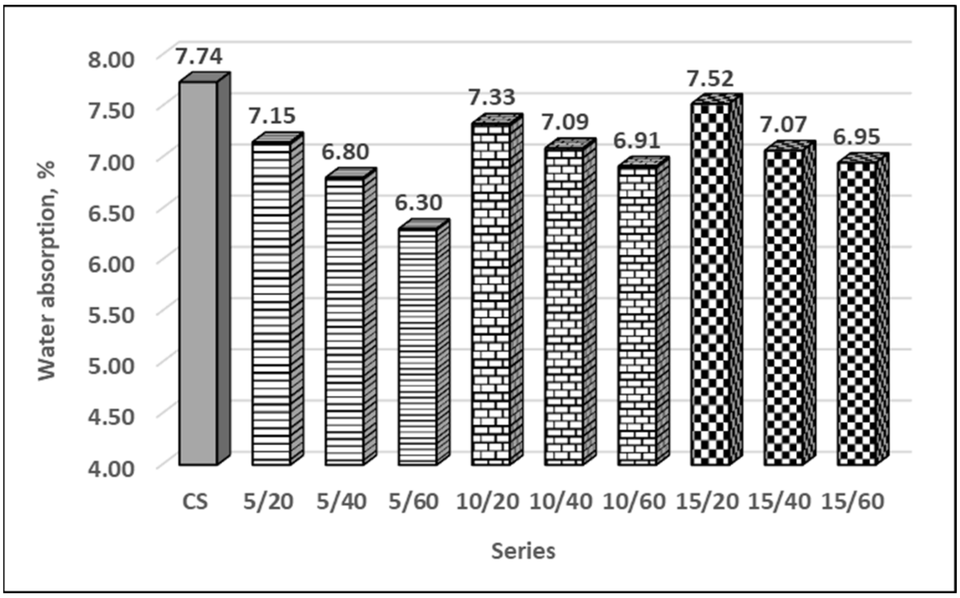


Figure 5. Water absorption of investigated cement mortar modified with waste polyamide 6.

3.3. Frost Resistance of Mortars Modified with Waste

Frost resistance tests of synthesized cement mortars were also carried out according to the PN-85/B-04500 standard [66]. The tested control cement mortars showed a decrease in compressive strength after 25 cycles of freezing and thawing by 5.49% (Figure 6). In each series of cement mortars modified with waste, the decrease in compressive strength was higher than for the control mortars. The highest decreases in compressive strength after frost resistance tests were achieved by the series of mortars containing the addition of 60% waste polyamide, regardless of the amount of fly ash contained in it. However, the lowest decreases in strength after frost resistance tests were observed for mortars containing 20% waste polyamide. Therefore, considering that the difference in strength loss for these series is in the range of 14.9–22.6%, the optimal value to be added can be 20% of waste polymer containing both 5, 10 and 15% of fly ash.

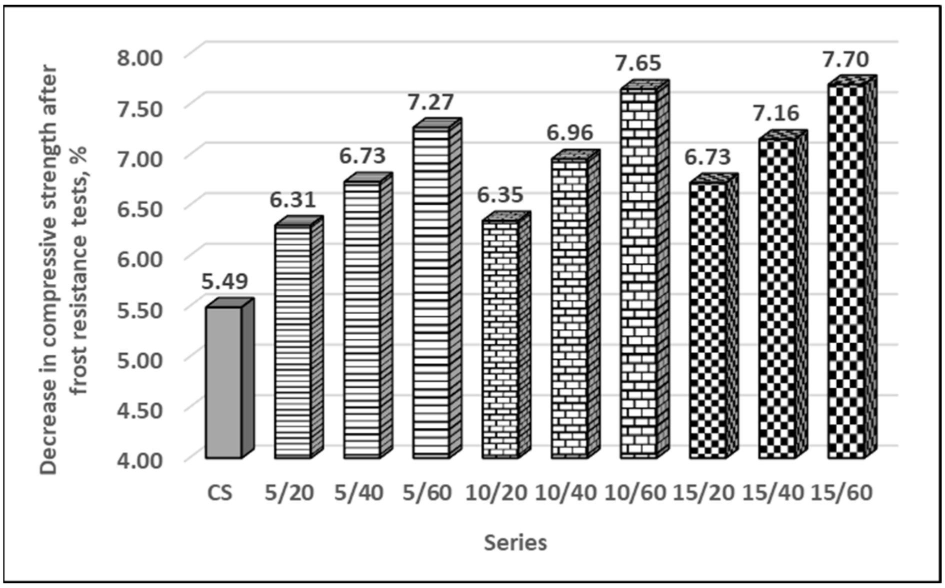


Figure 6. The compressive strength of investigated cement mortar after frost resistance tests.

3.4. Leaching of Metal Ions from Mortars Modified with Waste

Tests on the leaching of metal ions from cement mortars were carried out based on the PN EN-12457-2:2006 norm [67]. The test was performed for mortars modified with the highest waste content (60% polyamide containing 15% ash), assuming that they would have the highest content in the eluate. The determinations were made at a ratio of the volume of the liquid phase (L) to the mass of the solid phase (S) 10:1 The solid phase was cement mortar crushed to a size < 4 mm and the liquid phase was distilled water. The extraction was carried out for 24 h at room temperature under constant stirring. Calculations were made based on the standard, assuming no moisture in the samples. After the process of leaching ions from the control mortars, the pH of the solution was 9.89, while in the case of modified mortars, it was up to 9.92. The amount of toxic metal ions leached, such as zinc, lead, copper, chromium and barium, from mortars modified with polymer waste with fly ash filler is comparable to the amount of metal ions leached from control mortars (Table 4). The obtained concentrations of metal ions do not exceed the permissible values that must be met when introducing sewage into water and land, as well as when discharging rainwater or meltwater into water or water facilities, according to the Regulation of the Minister of Maritime Economy and Inland Navigation of 12 July 2019 (Journal of Laws 2019, item 1311) [68]. Therefore, the tested composite materials modified with waste do not pose a threat to the natural environment in case of cracking and damage. The slightly higher level of leaching of metal ions, i.e., Cu, Pb, Cr, Ba (but also below the level permitted by law) was observed for concrete produced with the addition of fly ash from biomass burning [5]. Also, the research by Kuterasińska-Warwas and Król [69] confirms that cement composite matrices immobilize heavy metal ions well. The authors showed that the new cement CEM II/C and CEM VI composite cement containing the addition of industrial waste are suitable for the use of matrices for the immobilization of heavy metals (Cu, Zn, Cr and Pb). The level of immobilization of Zn, Cu and Pb ions in the cement mortar matrix after 28 days was 100%, and of chromium—97.73%. The research showed a correlation between the composition of the used composite cement with the addition of waste and the melting and immobilization of heavy metals in the mineral matrices of mortars.

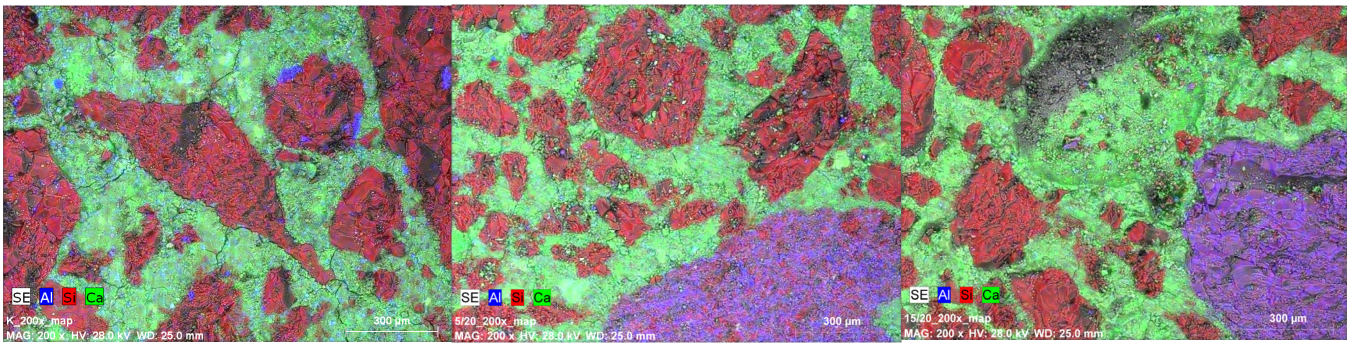
Table 4. Average ion leaching from cement mortar samples.

Metal Ions	Series				Limit Values, mg/dm^3
	SC		15/60		
	A, mg/kg	s	A, mg/kg	s	
Zn	<0.005	-	<0.005	-	2
Cu	0.087	0.013	0.119	0.021	0.5
Cr	<0.005	-	<0.005	-	0.5
Ba	0.114	0.016	0.132	0.039	2
Pb	0.096	0.014	0.116	0.017	0.5

A—the released amount of metal ions; s—standard deviation.

3.5. Microstructure of Cement Mortars Modified with Waste

In the next stage of the research, make use of the SEM (Scanning Electron Microscopy (LEO Electron Microscopy Ltd., Cambridge, UK)) equipped with an EDS chemical composition analysis system (based on X-ray energy dispersion), the surface of the synthesized composites was analyzed, mainly determining their morphology and elemental composition. Figure 7 shows microscopic photos taken on broken mortar surfaces along with maps of the distribution of dominant elements in this area. According to the analysis, both in the control mortar (CS) and in mortars containing the minimum (5/20) and maximum (15/60) amount of waste, a lighter structure of the cement matrix and darker places representing silicon-based aggregate are noticeable.



(**a**) (**b**) (**c**)

Figure 7. Microstructure of cement mortars with visible distribution of dominant chemical elements in this area at 200× magnification: (**a**) control mortar, (**b**) mortar containing 5% waste and (**c**) mortar containing 15% waste.

The visible microstructure at the aggregate-cement matrix interface is tight. EDS analysis of the mortar surface performed in the area shown in the photo showed, in addition to the presence of calcium (in the range of 7.3–31.7%; green), a significant content of silicon (9.6–45.3%, blue) and aluminum (0.5–0.8%; blue), and a small amount (less than 0.5%) of other components (Na, K, Mg, C, S, P). The structure of mortars modified with polyamide 6 waste containing fly ash from biomass combustion and their total chemical composition are similar to the control mortar. It can therefore be concluded that the addition of waste polyamide does not affect the microstructure of cement mortars. Similar observations were reported in [46] for mortars and [5,58] for concretes. It has been shown that the addition of hot-melted polyamide [46] to mortars or fly ash [5] and polyamide and polyethylene fibers [58] to concrete do not affect their microstructure. The work in [42] showed that the addition of recycled materials affects the microstructure of concrete, increasing its porosity.

3.6. Economic and Ecological Effectiveness of Using Waste Modifications

The use of various types of waste to produce building materials is not only a new research trend, but a necessity if we want the economy to move towards a circular economy. The use of fluidized fly ash to produce polyamide 6 with better physical and mechanical parameters, and the use of post-production waste for mortars, is not only ecologically but also economically effective. The economic effects of using fly ash waste from biomass combustion are both for the producer of this waste (he does not bear the costs of environmental fees for depositing it in landfills) and for producers of plastics and construction materials.

In the case of building materials such as mortars or concretes, unit profits (for 1 m^3) may not be large, but considering the large quantities of this type of materials produced annually, they should also be taken into account by entrepreneurs. Considering that the addition of 20 g of waste does not worsen the physical and mechanical properties of mortars, it allows for the replacement of 110 kg of sand in the production of 1 m^3 of cement mortar, which gives benefits of 2.6 EUR (assuming a sand price of 23.5 per Mg). Assuming the use of 60 g of waste (but obtaining mortars with lower strength parameters), we use about 330 kg less sand per 1 m^3, which translates into savings of 7.8 EUR. Translating this to concrete, where approximately 70% of the volume is aggregate and approximately 2 tons/m^3 is used, replacing each 10% of aggregate would allow for savings of approximately 4.7–11.6 EUR/m^3. Therefore, it is worth considering the use of this waste in cement mortars, and also considering their future use in concrete. Apart from the economic benefits, the use of fly ash from biomass burning for the synthesis of polyamide, and the post-production precipitation for the production of cement mortars, is advisable due to the need to protect natural resources and sustainable development.

4. Conclusions

The use of waste polyamide 6 collecting fly ash from the burning process of wood–palm kernel shells biomass in a circulating fluidized bed boiler for the fabrication of ecological construction materials is a desirable solution in the aspect of sustainable construction. The use of fly ash, which currently has no practical use for the synthesis of polyamide 6, and the subsequent use of polymer production waste to produce building materials should be treated as a desirable action toward a circular economy.

The conducted research on the properties and structure of cement mortars modified with production waste and the analysis of the obtained results allow us to conclude that the standard compressive and flexural strength of cement mortars (after 28 days of maturation) modified with a 20% addition of polyamide 6 containing 5% fly ash is higher by 6.6 and 4.9%, respectively, concerning control samples, and mortars with the addition of 40% production waste by 4.6 and 3.4%, respectively. Increasing the share of polyamide 6 waste in mortars, similar to increasing the share of fly ash in polyamide waste, has an adverse effect on the mechanical strength of cement mortars produced with their participation. All manufactured mortars with the addition of polyamide 6 waste modified with fly ash showed lower water absorption and mechanical strength after frost resistance tests. The microstructure of cement mortars modified with the addition of post-production polyamide 6 waste produced with biomass fly ash has a microstructure very similar to the control mortar. The use of this type of production waste is safe for the environment, as no leaching (release) of heavy metal ions into the environment from the produced cement mortars was observed. Heavy metal ions present in fly ash are incorporated into the synthesized polyamide 6, which allows for the safe use of post-production waste for the production of cement mortars and does not pose a threat in the event of damage or cracking of the eco-cement composite. For the production of cement mortars, it is recommended to add 20% polyamide waste containing 5% fly ash, which guarantees the maintenance of good mechanical parameters of the manufactured mortars necessary for construction products. The use of production waste polyamide 6 also has a positive impact on the natural environment by reducing the demand for natural raw materials. Using 20% of waste allows you to reduce sand consumption by 110 kg/m^3, which brings both economic and ecological benefits.

Author Contributions: Conceptualization: M.U. and A.G.; methodology: J.J. and A.G.; validation: M.U. and J.J.; formal analysis: M.U. and J.J.; investigation: J.J.; writing—original draft preparation: M.U., J.J. and A.G.; writing—review and editing: M.U.; visualization: J.J. and A.G.; supervision: M.U. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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