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The Influence of Waste Perlite Powder on Selected Mechanical Properties of Polymer–Cement Composites

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Abstract: The subject of this paper is the influence of the partial substitution of cement with mineral additive on the properties of polymer–cement composites (PCCs). Although there is considerable research on the use of perlite in cement concrete, most of the previous studies were conducted with expanded perlite or ground waste perlite, and there is a lack of results evaluating its suitability with polymer–cement composites. To fill this gap, this paper presents the mechanical characteristic of PCC mortars containing waste perlite powder. The modification consisted of replacing part of the cement with waste perlite powder, a byproduct formed during the expansion and fractionation of perlite. The granulometric characteristics of the powder were compiled, and its specific surface area and density were determined. A chemical composition analysis was also carried out. An aqueous dispersion of styrene–acrylic copolymer was used as a polymer modifier. The proportions (by mass) between the contents of the PCC composite components, i.e., cement/polymer (0 to 20%) and cement/mineral powder (0 to 15%), were used as material variables. The technical characteristics tested included the compressive, flexural, and tensile strengths at 28 and 90 days of curing. The compositions of the tested composites were determined using the statistical planning of the experiment. At a low polymer-modifier content in PCC mortars (2.93%), the tested mechanical strengths decreased by five times, with a 6-fold increase in waste content. For mortars containing more than 10% of the polymer modifier, no effect of waste material powder on the flexural strength was observed, while with relatively minor reductions in compressive strength of 2% and 5% and tensile strength of 4% and 2% were observed after 28 and 90 days of curing, respectively. It was shown that it is possible to use waste perlite powder as an ingredient in construction polymer–cement composites, while there is a limiting waste content, above which there is a deterioration in mechanical properties.

Keywords: polymer–cement composite; strength; utilization; waste perlite powder

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1. Introduction

Polymer–cement concretes and mortars (PCCs) are included in the group of concrete-like composites in which a polymer modifier is incorporated alongside the cement binder. Now widely used in the construction industry, this material was introduced in the 1920s, when natural polymers—rubber latexes—began to be used. The first patent for the addition of such latex to improve road pavement material was granted in 1923 in the UK (L. Cresson), while the first patent presenting the modern concept of a polymer–cement binder was obtained by V. Lefebure in 1924 [1].

Polymer–cement composite manufacturing technology is similar to the technology used to obtain conventional cement concrete. The polymer-modifier content is usually in the range of 10 ÷ 20% of cement mass. At the same time, it should be noted that only a small number of polymers are suitable for the modification of a cement binder. In particular, the presence of a polymer modifier increases the flexural and tensile strength of the composite and reduces its permeability [2]. The chemical and frost resistance, and therefore the durability of the product, is improved.

A particular area of polymer–cement composites application is the repair and protection of concrete structures [3,4], the manufacturing of industrial pavements and floors [5], and the fabrication of prefabricated elements [6]. The main impediment to applying polymer–cement composites is their relatively high material cost, although lower than resin cementless composites, due to the smaller amount of polymer required in their manufacturing. A desire to reduce material costs, while maintaining material performance, is driving the search for new material solutions [2,7]. One of the methods used to reduce the material cost is to replace some of the components with cheaper substitutes, both natural raw materials and waste materials.

Although the use of waste materials in the construction industry, especially in cement concrete technology, is considerable [8–11], mineral additives have long been considered incompatible with polymeric binders [12]. Ensuring a good interaction between mineral ashes and polymers in polymer–cement composites is, therefore, an important scientific problem; solving it will also have practical implications.

An example of such a material is waste perlite powder, a byproduct of the expansion and fractionation of natural perlite. Due to its specific structure, expanded perlite is characterized by, among other things, low density, the ability to absorb liquids and gases, and above all, a very good thermal and acoustic insulating capacity. These characteristics have influenced its widespread usage as a lightweight filler for building materials such as plasters, mortars, etc.

The introduction of expanded perlite into concrete adversely affected the consistency of the concrete mixture [13]. This is due to the increased water demand of the material, resulting from the high content of perlite particles with small diameters (<315 μm), but also the high aeration of the mixture [14]. Similarly, when using a large amount of ground waste perlite, replacing 35% of the Portland cement with perlite resulted in a 25% increase in water demand, negatively affecting the consistency of the mortar [15].

The introduction of perlite into the concrete also affects the binding process. Ground waste-expanded perlite (WEP) is a highly effective pozzolanic additive for cement-based materials. It remarkably decreases the concentration of calcium hydroxide in the hydrating pastes while increasing the proportion of hydration products other than calcium hydroxide. Incorporating ground WEP leads to a notable enhancement in the rate of hydration during the acceleration period; however, it tends to slow down the hydration process over long periods [16].

Divergent views on the effect of expanded perlite on the mechanical properties of composites can be found among researchers. Sengul et al. [17], in their study, used expanded perlite as a substitute for natural aggregate in lightweight concretes. When natural aggregate was completely replaced with expanded perlite, the compressive strength of these concretes was up to 99% lower, compared to the control sample. Using expanded perlite powder as an additive is a great way to create a mortar for rendering tasks that is easy to work with. When expanded perlite is used, the mortar's lifespan is extended, and its ability to retain water is slightly improved when used in small amounts. The reason for this improvement is the perlite's natural inclination to hold onto water within its internal voids. Moreover, expanded perlite reduces the overall density of the mortar, resulting in better workability. However, when higher amounts of perlite are added, the amount of water needed for mixing increases significantly from 21.0% to 48.9%, which negatively impacts the mechanical performance [18]. In contrast, according to Erdogan and Saglik [19], perlite can be used to replace 25 ÷ 50% of Portland cement without significant strength loss. In addition, according to these authors, it is possible to influence the improvement of the strength of perlite-modified mortars by activating them with solutions of $CaCl_2$, Na_2SO_4, HCl, or Na_2SiO_3. A similar finding proving the positive effect of using waste-expanded perlite on mechanical strength was observed by Łagosz et al. [20]. In most instances, the durability of mortars that were mixed with ground waste-expanded perlite was higher than that of the control sample, which consisted only of cement. Strength improvements were observed in all the mortars, including those with a high slag content. The mechanical properties of construction composites are influenced, among others, by the pozzolanicity of the mineral additive. The pozzolanic properties of perlite were investigated by a team led by L.-H. Yu [21], and they demonstrated significant pozzolanic properties of natural perlite, which depend on both the maturity time of the concrete and the water/cement ratio. According to Urhan [22], the pozzolanic activity of perlite can cause an increase in the strength of the transitional zone between the cement matrix and the lightweight aggregate, which is perlite. On the other hand, Demirboga et al. [23] attribute the improvement in the strength of concretes containing perlite as an aggregate not only to the pozzolanic properties of this volcanic glass but also to its function as a filler for empty spaces. Erdem et al. [24] also confirmed the pozzolanic character of perlite in their research. They found out that the silica content in the chemical composition of perlite, the amorphous structure of the material demonstrated via X-ray diffraction analysis, and the compatibility of the perlite test results with the specifications of natural pozzolans according to the American Standard ASTM C 618-08a [25] confirmed the pozzolanic properties of perlite.

The significant production of expanded perlite (520,000 tons in 2020 in the United States alone [26]) has generated a large amount of waste. With unfavorable morphological properties and a very low bulk density, waste perlite powder is cumbersome and expensive to dispose of [27].

Waste perlite powder is a byproduct of the perlite expansion process. Large amounts (about 5–10%) of the dusty fraction, waste perlite powder, which is difficult to dispose of, are then formed. As an example, an average manufacturing facility generates about 3–8 thousand m^3 of waste per year. The estimated amount of waste perlite powder generated in Poland is about 20–25 thousand m^3 per year. Currently, this waste is most often disposed of via storage on site (usually in so-called "big bags") or through partial addition to coarser-grained perlite, which, however, deteriorates the performance of the latter. Due to the large volume of waste generated, the possibilities for storing it on production sites are slowly running out. It involves incurring additional costs to find new areas that can be used for storage, and it also increases the environmental fees incurred by the production facility. The few attempts to use this waste are one offs and do not solve the problem. In addition, the problem of managing this troublesome waste product also arises for entities that use expanded perlite as an ingredient in manufactured products, e.g., as a lightweight filler for plaster, where the finest fractions are also separated from the expanded perlite due to the problems that arise during use because of their excessive proportion.

One way to dispose of this waste may be to introduce it as a mineral additive to Portland cement. This approach was proposed by Kapeluszna et al. [15]. In their study, in which they replaced part of the cement with ground waste perlite, they demonstrated the waste's favorable pozzolanic properties. However, the authors point out that at a high waste content (35% by cement mass), the water absorption of the cement increased significantly, necessitating the use of a superplasticizer.

Another way of utilizing this waste was proposed by Łukowski et al. [28], introducing it into resin ("cement-free") composites. The results of the study allowed a positive assessment of the possibility of utilizing this type of waste in polymer composites. The authors note, however, that as a result of the irregular grain shapes of the waste, and the resulting increased surface area, a larger amount of polymer binder must be used to provide suitable conditions for filler and binder adhesion.

Considering the above, it is reasonable to search for material and technological solutions to apply this waste to the production of construction materials. The disposal of mineral wastes is part of a sustainable development strategy, according to which, among other goals, the consumption of matter should be minimized, elements and materials should be reused, and waste should be managed efficiently.

The purpose of this study was to address the scientific problem of the influence of mineral waste—waste perlite powder—on the properties of polymer–cement composites.

Most of the previous studies were conducted with expanded perlite or ground waste perlite, and the material was used in the cement concrete. There is a lack of results evaluating the suitability of waste perlite powder (without grading) in polymer–cement composites. The presented paper is designed to fill this gap and give information on the influence of waste perlite powder on the mechanical strengths of polymer–cement composites. Therefore, a multi-stage experimental program was planned, allowing us to determine the conditions for the substitution of cement with the considered mineral powder, along with an analysis of the effects of such a change.

2. Materials and Methods

2.1. Polymer Modifier

Among the polymer modifiers used in the construction industry, an aqueous dispersion, styrene–acrylic (SA) copolymer, was chosen for the study. This copolymer is recommended by the manufacturer (MC-Bauchemie) for refining cement screeds and bonding layers. Previous studies on using perlite [15,28] have shown its increased water demand and the resulting issues with the workability of the mixture. Therefore, a dispersion that improves strength, has a liquefying effect, and reduces the risk of crack formation was chosen. The selected aqueous dispersion was characterized by 34.4% polymer content and a density equal to 1.014 g/cm^3.

2.2. Mineral Addition

Waste perlite powder (P), a byproduct of perlite expansion obtained at the "Piotrowice II" production plant (Poland), was used in this study.

The results of determining the distribution of grain size, specific surface area, and density of the mineral additive under consideration are shown in Table 1. In addition, Table 1 presents a statistical analysis of the grain size distribution of mineral powder.

Table 1. Density (ρ), grain size, and specific surface area (S.P) of waste perlite powder and statistical analysis of the grain size distribution.

ρ g/cm^3	D_{min}, μm	D_{max}, μm	S.P., cm^2/cm^3	Mean, μm	Median, μm	Variance, μm^2	CV, %	Mode, μm	D_{50}, μm	D_{90}, μm
2.24	4.5	116.2	2123	37.0	35.1	286.2	45.8	36.8	39.2	59.0

A statistical analysis was presented for each of the grain size distributions, including the mean value, coefficient of variation and median, variance and distribution modes, and D_{50} and D_{90}—the diameters that 50% and 90% of the grains of a given mineral powder do not exceed—were recorded.

Waste perlite powder was characterized by high minimum grain size. The great proportion of fractions with higher diameters resulted in a small specific surface area of the waste. It was characterized by a creamy white color, a pH of 7.8, and the density of 2.24 g/cm^3. The waste perlite powder activity index, measured according to PN-EN 450-1 [29], was 14.4% and 13.2%, respectively, after 28 and 90 days of curing.

The chemical composition of waste mineral powder, as determined via XRF, is shown in Table 2.

Table 2. Chemical composition (in %) of waste perlite powder used in the study.

SiO_2	Fe_2O_3	Al_2O_3	TiO_2	CaO	MgO	SO_3	P_2O_5	Na_2O	K_2O	Cl	F	LOI
73.74	1.25	13.12	0.08	1.23	0.03	0.01	0.02	3.42	4.20	0.07	0.05	2.78

Microscopic photographs of waste perlite powder are presented in Figure 1. Chosen particles of waste perlite powder exhibit a variety of shapes, including plate-like, spherical, and irregular forms. Microscopic examinations have substantiated that these particles are not circular in shape. Although the measurements recorded using the laser particle size distribution analyzer are accurate, they represent the greatest dimensions of plate-like or cylindrical structures, rather than the diameters of circular grains.

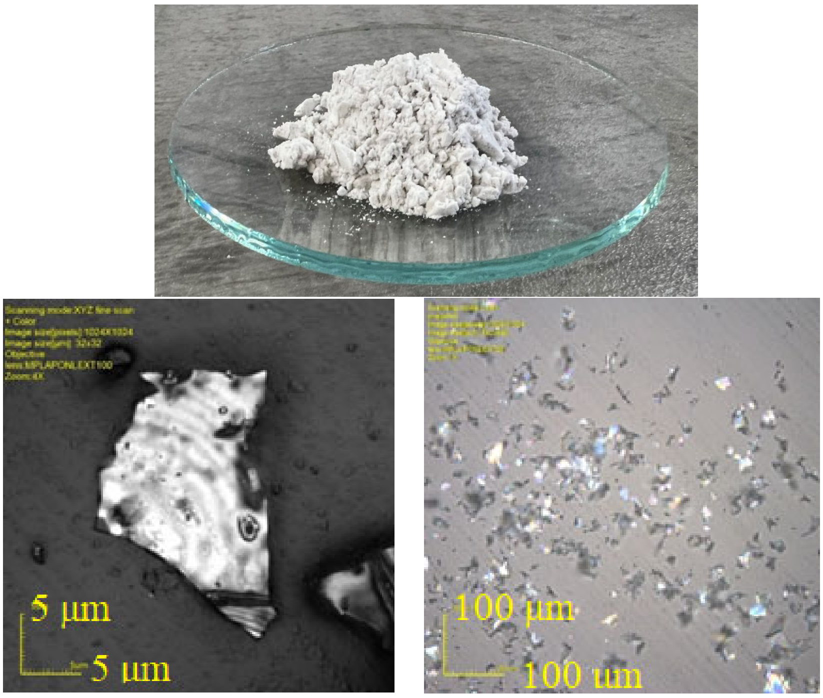

Figure 1. Waste perlite powder and its microscopic photograph—selected grains.

The chemical composition of waste mineral powder is shown in Table 2.

2.3. Cement

For the preparation of the specimens, Portland cement (CEM I 42.5R Lafarge, Małogoszcz, Poland) with high early strength and composition in accordance with the PN-EN 197-1 [30] requirements was used.

2.4. Sand

Standard sand (Kwarcmix, Poland) was used as the main aggregate according to CEN, meeting the requirements of PN-EN 196-1 [31].

2.5. Test Methods

The grain size distribution and specific surface area of waste perlite powder were determined using the Horiba LA300 (Horiba Scientific, HORIBA Instruments, Singapore) laser grain-size analyzer. The measurement method involves analyzing scattered laser light in a dispersing solution containing dissolved particles of the material under consideration, while simultaneously determining the average particle size in the mixture. A water solution of sodium polymetaphosphate $(NaPO_3)x$ at a concentration of 0.1% was used as the dispersing medium. Mineral powder was analyzed under the following parameters: refractive index 1.16-0.00i, pump circulation speed 7.0 L/min, and the duration of ultrasonic dispersion application of approximately 1 min.

The density of waste perlite powder was determined using a Le Chatelier flask (Multiserw, Marcyporęba, Poland) according to the Polish Standard PN-B-06714-02 [32], with three repeated measurements. The study involved adding the tested material to a specified volume of the flask containing ethyl alcohol.

The chemical composition analysis was conducted using the Thermo iCAP 6500 Duo ICP (SpectraLab, Markham, ON, Canada) plasma spectrometer.

The mechanical properties of specimens were studied after 28 and 90 days of curing.

The flexural strength was measured on three specimens with dimensions of 40 × 40 × 160 mm in accordance with Polish Standard PN-85/B-04500 [33]. The measurement, which consisted of loading the specimen with a concentrated force at the center of the span, with a support spacing of 100 mm, until fracture, was performed using the testing machine INSTRON 567 (Instron, Opole, Poland), and the rate of load increment was 3000 N/min.

The compressive strength testing was carried out in accordance with PN-85/B-04500 [33] on the six halves of the beams remaining after the flexural strength test. Measurement was performed using a CONTROLS (Controls, Milan, Italy) testing machine.

Tensile strength testing of polymer–cement mortars was carried out on three "figure-eight"-shaped specimens with a cross-section at the thinnest 22.5 × 22.5 mm, in accordance with PN-85/B-04500 [33]. The measurement consisted of subjecting the sample to tension in the direction of the longitudinal axis in a testing machine, INSTRON 567, until it ruptured. The rate of load increase was 600 N/m.

Microstructural examinations were carried out using a Scanning Electron Microscope PRISMA E (Thermo Fisher Scientific, Waltham, MA, USA), applying a reflected electron detector. Observations were made at magnifications of 1500× and 500×.

A solution of the copolymer in water was combined with the dry components and the appropriate amount of tap water to achieve the desired water/cement ratio (w/c = 0.5). Once all the ingredients were thoroughly mixed, the mixture was poured into molds and covered with foil. After 24 h, the molds were opened, and the specimens were further treated. The PCC composites were immersed in water for 5 days and then left to dry in the air for the subsequent days. This allowed the formation of a polymer–cement matrix after cement hydration in the initial period of curing.

3. Modified Polymer–Cement Composite Material Design Model

3.1. Research Program and Methodology

In order to determine the possibility of using waste mineral powders as building components in polymer–cement composites, composites were designed based on the statistical planning of the experiment. Planning experiments, as one of the tools of statistical quality control, makes it possible to identify the factors most strongly affecting the variable characterizing the process under study, as well as making it possible to indicate the values of the factors for which the outcome variable achieves the desired value or the lowest variability. A two-factor polysolution-rotal-quasi-uniform plan with a two-fold repetition of the central point was used.

Selecting a two-factor plan (rather than a complete plan) to design composites containing waste perlite powder allowed us to characterize the effects of this mineral additive on the properties of PCC composites using fewer experimental points. This powder had a much higher volatility, resulting in difficulties in the dosing and homogenization of the mixture.

As part of the development of the experimental plan for polymer–cement composites containing waste mineral powders, a set of quantities characterizing the test object was defined and divided into input quantities and output quantities. The input variables describing the composites' composition were the polymer content (p/c) in the range from 0% to 20% (by cement mass), and the mineral powder content (m/c) in the range from 0% to 15% (by cement mass). The range of variability of the input values was selected on the basis of the preliminary laboratory tests, which included selecting the appropriate polymer modifier, determining the maximum amount of polymer, and determining the maximum amount of waste perlite powder.

The flexural strength, the compressive strength, and the tensile strength were used as the diagnostic characteristics (output variables).

3.2. PCC Composites Containing Waste Perlite Powder

Applied in the research is a plan with a two-fold repetition central point, which includes 10 measurement points. The central point was repeated twice in order to achieve better precision in the material model developed on the basis of the tests carried out according to this plan.

Given the ranges of variation adopted for both variables (for p/c (x_1): 0 ÷ 20% and for m/c (x_2): 0 ÷ 15%) the corresponding actual values of the variables were determined. A summary of the coded values and the corresponding actual values, as well as the material compositions of the tested mortars (compositions per kg of mortar) are summarized in Table 3.

Table 3. The coded values, corresponding actual values, and material compositions of the tested mortars.

No.	Coded Values		Actual Values		Proportion of the Ingredients, g				
	x_1	x_2	p/c, % (x_1)	m/c, % (x_2)	Polymer (SA)	Perlite Powder (P)	Cement	Water	Sand
1	−1	−1	2.93	2.20	6.5	4.9	215.9	110.4	662.3
2	−1	1	2.93	12.80	6.5	28.3	192.5	110.4	662.3
3	1	−1	17.07	2.20	36.5	4.7	209.4	107.1	642.3
4	1	1	17.07	12.80	36.5	27.4	186.7	107.1	642,3
5	−1.414	0	0	7.50	0.0	16.7	205.5	111.1	666.7
6	1.414	0	20.00	7.50	42.6	15.9	196.8	106.4	638.3
7	0	−1.414	10.00	0	21.7	0.0	217.4	108.7	652.2
8	0	1.414	10.00	15.00	21.7	32.6	184.8	108.7	652.2
9	0	0	10.00	7.50	21.7	16.3	201.1	108.7	652.2
10	0	0	10.00	7.50	21.7	16.3	201.1	108.7	652.2

4. Results and Analysis

4.1. Flexural Strength

Values for flexural strength of up to 11.0 MPa after 28 days of curing were received for all PCC composites containing waste pearlite powder. The exception was composite No. 2, for which the value of flexural strength did not exceed 3.5 MPa (Table 4). For none of the compositions did the coefficient of variation exceed 10%, indicating good precision in the determinations [34]. Composite No. 2, which contains 12.8% waste pearlite powder and 2.93% polymer (by cement mass), was characterized by the lowest flexural strength (f_b = 3.2 MPa).

Table 4. Flexural strength of PCC mortars with different contents of styrene–acrylic copolymer (SA) and different contents of waste perlite powder (P) specimens after different curing times (SD—standard deviation, CV—coefficient of variation).

No.	p/c, %	m/c, %	Flexural Strength, MPa					
			28 Days			90 Days		
			Average	SD	CV, %	Average	SD	CV, %
1	2.93	2.20	9.3	0.9	9.4	9.7	0.2	2.1
2	2.93	12.80	3.2	0.1	1.8	3.4	0.2	6.1
3	17.07	2.20	11.0	0.2	1.9	13.0	0.3	2.3
4	17.07	12.80	10.9	0.4	3.3	12.0	0.5	4.2
5	0.0	7.50	8.1	0.2	0.0	8.4	0.5	5.9
6	20.0	7.50	10.3	0.2	2.0	12.0	0.7	5.4
7	10.0	0.0	10.4	0.5	4.8	11.9	0.1	0.8
8	10.0	15.0	9.2	0.6	6.0	10.4	0.1	0.7
9	10.0	7.50	10.3	0.2	1.7	10.1	0.9	8.9
10	10.0	7.50	10.4	0.3	0.0	10.9	0.4	3.5

For compositions with the same percentage of polymer (p/c = 2.93%), but differing in the content of perlite, a significant effect of the waste content on the flexural strength of the PCC was observed (Figure 2). The addition of waste pearlite powder to the other composites did not significantly affect their flexural strength. Compositions with the same content of waste pearlite powder, but differing in the amount of polymer modifier, differed slightly in strength (with the exception of the aforementioned composite with p/c = 2.93%), with the composite with the lowest waste content and high polymer amount having the highest flexural strength—p/c = 17.07% and m/c = 2.20% (Table 4 and Figure 2).

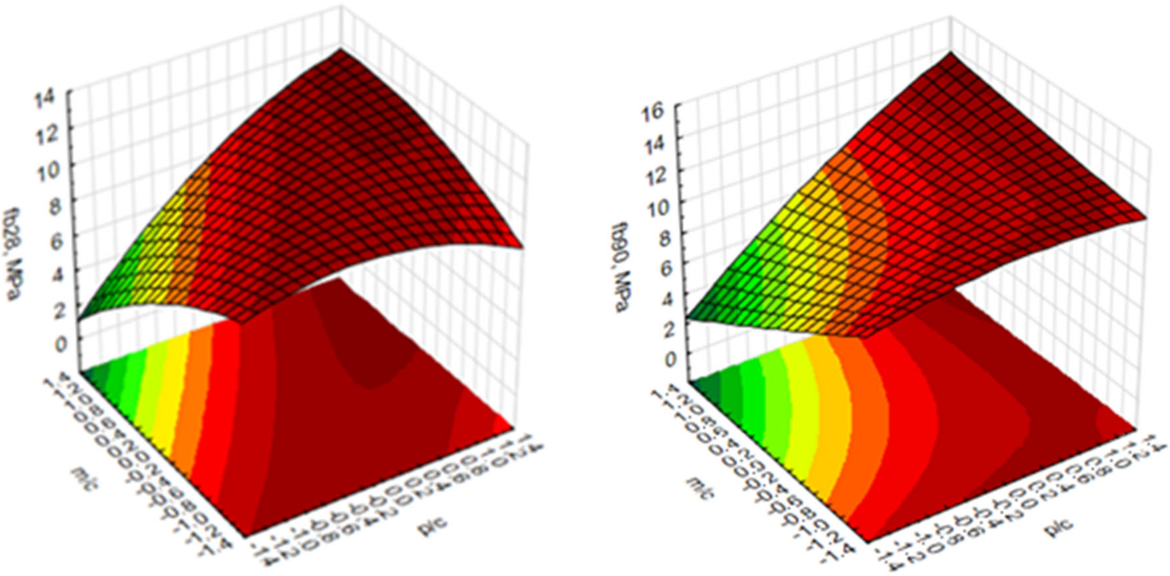

Figure 2. Flexural strength of PCC mortars with different contents of styrene–acrylic copolymer SA and different contents of waste pearlite powder (standardized values)—specimens after 28 days of curing (**left**) and 90 days of curing (**right**).

For the composites tested after 90 days of curing, higher flexural-strength values, compared to 28-day specimens, were obtained, but not more than 13.0 MPa. The exception is also composite No. 2, for which the flexural strength value did not exceed 3.5 MPa (Table 4). For none of the compositions did the coefficient of variation exceed 10%, indicating good precision in the determinations. In this case, composite No. 2 (f_b = 3.4 MPa) also has the lowest flexural strength, and the effect of the content of waste pearlite powder can best be observed for compositions with an equal percentage of polymer (p/c = 2.93%) (Figure 2). After 90 days, the composite with the lowest waste content and high polymer content—p/c = 17.07%, m/c = 2.20%—is characterized by the highest value for flexural strength (Table 4 and Figure 2).

4.2. Compressive Strength

Values for compressive strength of up to 40.0 MPa after 28 days of curing were recorded for all PCC composites containing waste pearlite powder. The exception is composite No. 2, for which the compressive strength value did not exceed 7.8 MPa (Table 5). Only for composites containing different amounts of waste perlite powder, but modified with the smallest amount of polymer (p/c = 2.93%), was the effect of waste on the compressive strength of polymer–cement mortars observed (Table 5, Figure 3).

After 90 days of curing, an increase in the compressive strength of the tested composites was observed (Table 5). As was the case with the specimens tested after 28 days, after 90 days, the most significant effect of waste pearlite powder was observed for composites with the lowest polymer-modifier content (Figure 3).

An analysis of the presented results indicated the influence of the waste mineral powders on the mechanical properties, in particular, on the compressive strength. The presence of mineral additives in the amount of >25% by cement mass caused a deterioration in the strength parameters of the composites, especially those containing a small amount of polymer modifier (p/c = 5 ÷ 10%).

Table 5. Compressive strength of PCC mortars with different contents of styrene–acrylic copolymer (SA) and different contents of waste perlite powder (P) specimens after different curing times (SD—standard deviation, CV—coefficient of variation).

No.	p/c, %	m/c, %	Compressive Strength, MPa					
			28 Days			90 Days		
			Average	SD	CV, %	Average	SD	CV, %
1	2.93	2.20	42.1	0.9	2.0	46.8	0.8	1.8
2	2.93	12.80	7.8	0.6	8.3	9.1	0.9	9.6
3	17.07	2.20	38.7	0.5	1.2	48.0	0.9	1.9
4	17.07	12.80	37.9	0.9	2.4	45.3	0.4	0.8
5	0.0	7.50	37.4	2.2	5.8	40.1	1.4	3.5
6	20.0	7.50	33.6	0.9	2.8	41.9	0.8	2.0
7	10.0	0.0	40.1	0.7	1.7	47.7	0.5	1.1
8	10.0	15.0	35.5	1.0	2.7	39.9	1.6	3.9
9	10.0	7.50	41.1	1.6	3.9	46.3	1.8	3.8
10	10.0	7.50	39.6	2.3	5.7	43.5	1.0	2.3

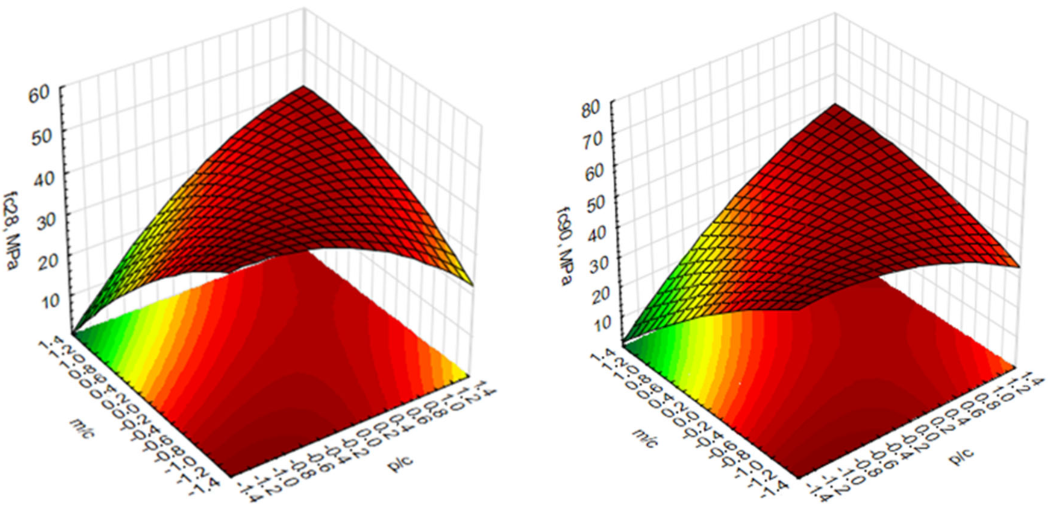

Figure 3. Compressive strength of PCC mortars with different contents of styrene–acrylic copolymer SA2 and different contents of waste pearlite powder (standardized values)—specimens after 28 days of curing (**left**) and 90 days of curing (**right**).

4.3. Tensile Strength

In the case of the tensile-strength test, composite No. 2 obtained the lowest strength values of 0.9 MPa and 1.2 MPa, respectively, after 28 and 90 days of curing (Table 6). The most significant effect of waste on the tensile strength of the polymer–cement mortars was observed for composites containing 2.93% polymer modifier (Figure 4). For composites with a constant amount of polymer of 10%, a slight decrease in tensile strength was observed with an increase in the content of waste perlite powder (Table 6 and Figure 4). An increase in tensile strength was observed for composites with a constant amount of waste (m/c = 7.5%) and variable modifier content (Figure 4).

Table 6. Tensile strength of PCC mortars with different contents of styrene–acrylic copolymer (SA) and different contents of waste perlite powder (P)—specimens after different curing times (SD—standard deviation, CV—coefficient of variation).

No.	p/c, %	m/c, %	Tensile Strength, MPa					
			28 Days			90 Days		
			Average	SD	CV, %	Average	SD	CV, %
1	2.93	2.20	4.4	0.1	2.3	4.5	0.2	3.8
2	2.93	12.80	0.9	0.0	0.0	1.2	0.1	4.7
3	17.07	2.20	5.2	0.1	1.9	5.7	0.1	1.0
4	17.07	12.80	5.0	0.4	8.1	5.6	0.1	1.8
5	0.0	7.50	3.7	0.3	9.4	3.8	0.1	1.5
6	20.0	7.50	4.9	0.2	3.5	5.4	0.0	0.0
7	10.0	0.0	4.8	0.4	8.5	5.2	0.1	1.9
8	10.0	15.0	4.2	0.1	2.8	4.7	0.2	3.2
9	10.0	7.50	4.7	0.1	1.2	4.8	0.1	1.2
10	10.0	7.50	4.5	0.1	1.3	4.8	0.1	1.2

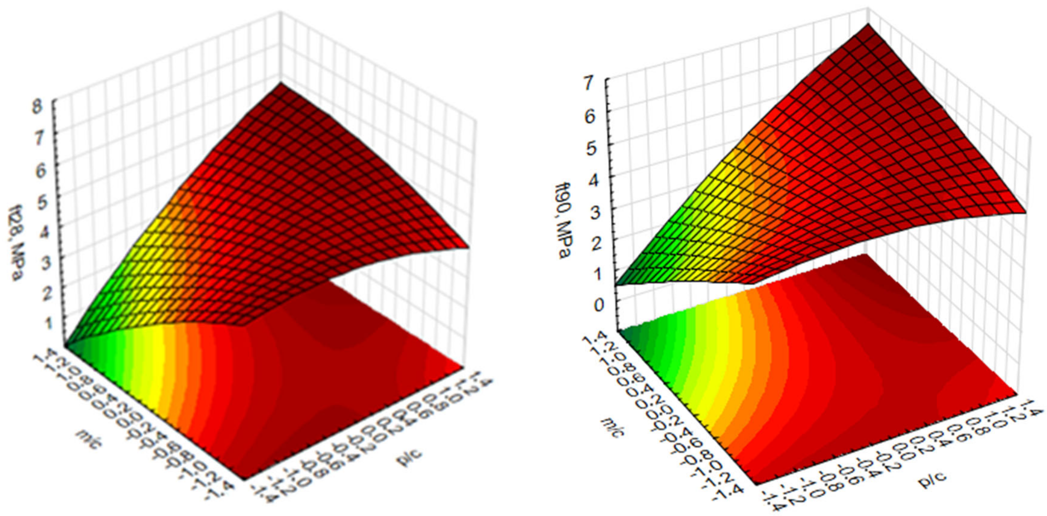

Figure 4. Tensile strength of PCC mortars with different contents of styrene–acrylic copolymer SA and different contents of waste pearlite powder (standardized values)—specimens after 28 days of curing (**left**) and 90 days of curing (**right**).

Figures 5 and 6 summarize the effect of the cement substitution with waste perlite powder on the mechanical strengths. The partial replacement of cement with waste perlite powder, in general, results in decreased mechanical strength in PCC mortars. In the case of mortars containing more than 10% of polymer modifier, waste perlite powder introduction does not have a significant effect on mechanical strengths when the waste content is increased. This could be related to the formation of a polymer film, which increases the strength of the binder interface between the cement hydration products and the aggregate [35]. The observed mechanical characteristics of PCC specimens in this case appear to be more influenced by the quantity of the polymer modifier, rather than the presence of waste perlite powder. The waste perlite powder influence becomes marked in the case of PCC mortars with a small amount of polymer modifier. In those mortars, the introduction of 6 times more waste resulted in a reduction in the flexural strength by 3 times, the compressive strength by 5 times, and the tensile strength by 4.5 times. As could be suspected [18], lightweight aggregates, despite their pozzolanic properties, modify the mortar's mechanical characteristics by decreasing its flexural and compressive strength. In the research presented in this paper, waste perlite powder, which was characterized by a low activity index and a small specific surface area, was applied. In addition, the waste was not subjected to any mechanical treatment, such as grinding. All of this may have the effect of weakening the cement hydration and polymer film formation processes. This is in agreement with reported research, which concluded that the reduction in strength could be due to the decelerating effect of polymer modifiers on cement hydration, the volume change of the mortar [36,37], and less integrity between the binder and perlite [38]. Also, perlite use in the concrete mixture leads to an increase in porosity, which leads to lower density and reduced strength [39,40]. The studies presented in [41,42] yielded comparable results.

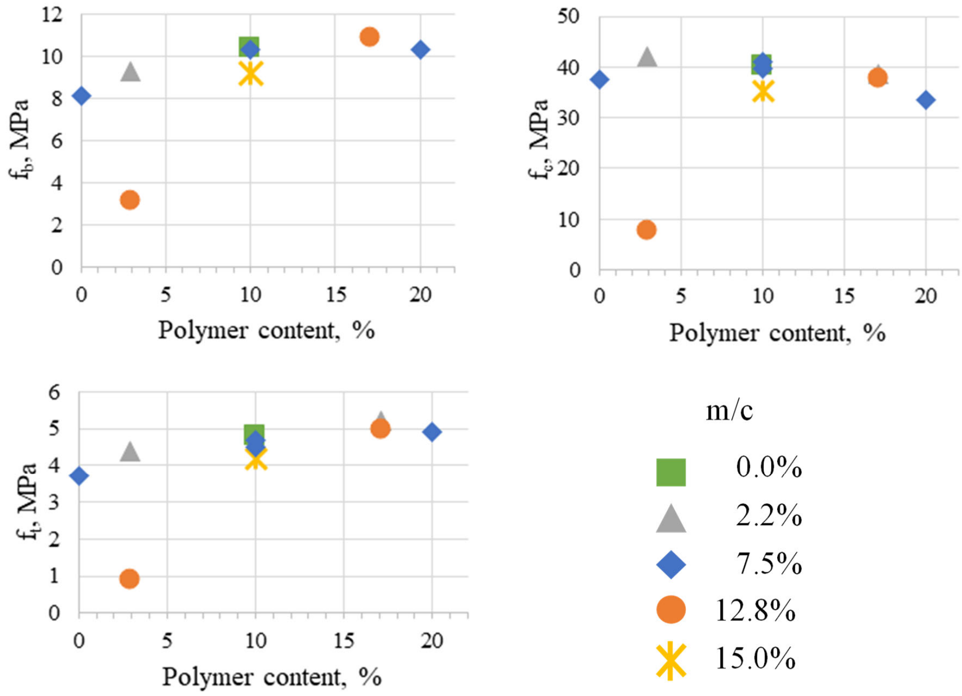

Figure 5. Tested mechanical strengths of polymer–cement composites containing various amounts of waste perlite powder (m/c) after 28 days of curing.

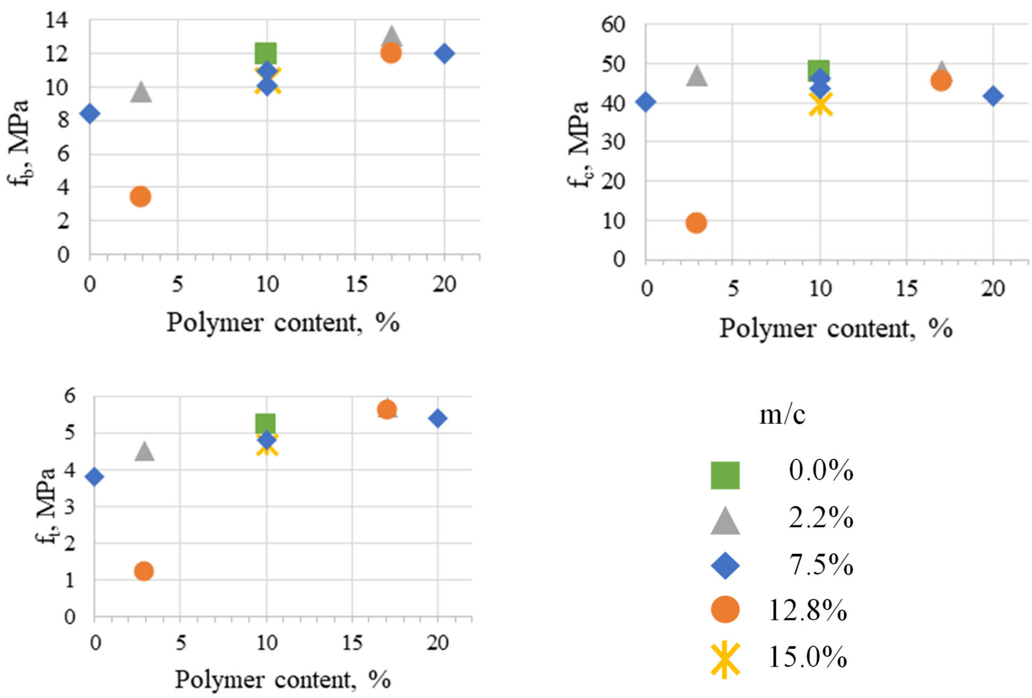

Figure 6. Tested mechanical strengths of polymer–cement composites containing various amounts of waste perlite powder (m/c) after 90 days of curing.

4.4. Microstructural Observations

Microstructural examinations were carried out using a scanning electron microscope (SEM), applying a reflected electron detector. Observations were made at magnifications of 1500× and 500×. The microscopic images present the microstructure of polymer–cement composites containing waste perlite powder. The microstructure of the composite as porous and irregularly shaped grains of waste pearlite powder can be seen situated in the composite (Figure 7).

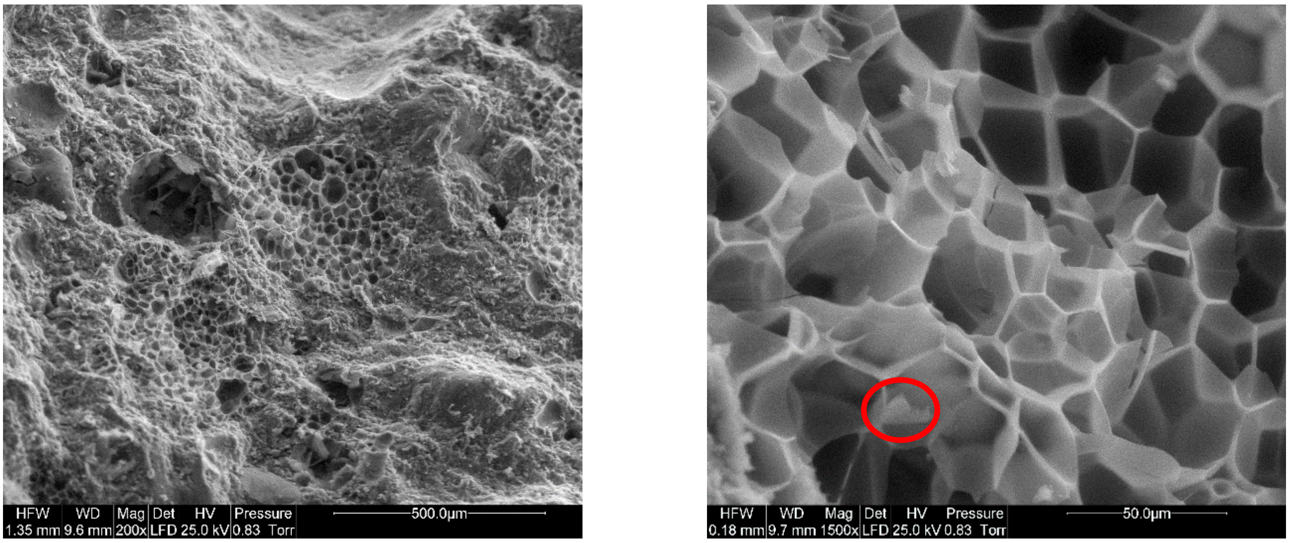

Figure 7. Polymer–cement composited with waste perlite powder—in the red circle, we can see a perlite powder grain with a characteristic blade-like shape.

5. Conclusions

The purpose of this study was to determine the effect of the presence of waste perlite powder, which is produced during the expansion and fractionation of perlite, on the mechanical properties—flexural, compressive, and tensile strength—of polymer–cement mortar. For this purpose, a multi-stage experimental program was planned to assess the determinants of cement substitution with a mineral additive, and to analyze the effects of such a change. Based on the results obtained in the study, the following conclusions can be drawn:

1. Cement substitution with waste perlite powder did not deteriorate the flexural strength of the PCC mortars containing more than 10% of the polymer modifier. At a low polymer-modifier content in PCC mortars (2.93%), the flexural strength decreases by 65% with a 6-fold increase in waste content.
2. Considering the compressive strength, a minor reduction of 2% and 5% after 28 and 90 days, respectively, was observed for the PCC mortars containing more than 10% of the polymer modifier. At a low polymer-modifier content in PCC mortars (2.93%), the compressive strength decreases by 81% with a 6-fold increase in waste content.
3. Considering the tensile strength, a minor reduction of 4% and 2% after 28 and 90 days, respectively, was observed for the PCC mortars containing more than 10% of the polymer modifier. At a low polymer-modifier content in PCC mortars (2.93%), the tensile strength decreases by 73% with a 6-fold increase in waste content.
4. Waste perlite powder can be used as a substitute for part of the cement binder in polymer–cement composites; such composites have technical characteristics similar to conventional polymer–cement composites.
5. The mechanical properties of polymer–cement composites containing waste pearlite powder depend more on the content of the polymer modifier than on the presence of the powder at higher polymer contents in mortars.

Most of the previous studies were conducted with expanded perlite or ground waste perlite, and the material was used in the cement concrete. There is a lack of results evaluating the suitability of waste perlite powder in polymer–cement composites. In addition, the waste perlite powder that was used in this study was characterized by a low activity index and a small specific surface area and was not subjected to any mechanical treatment such as grinding.

Even though mechanical strength is extremely important in cementitious materials, PCC mortars used as protection for concrete structures are not intended or created for structural functions. The studies presented in the paper revealed a minor reduction in PCC mechanical strength after incorporating the waste perlite powder (except for the specimens with a low content of polymer modifier), thereby pointing to a new direction in the use of these troublesome materials.

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