

Article

Analysis of the Influence of PET and Glass Packaging Waste Materials on the Physical and Mechanical Properties of Cementitious Composites

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Abstract: The limited availability of natural resources, such as sand, and the need to reduce CO₂ emissions, which are produced in large quantities in the production of binding materials, indicate the need to look for alternative raw materials used in construction materials. At the same time, there is a strong need to utilise waste packaging materials, the global production of which is constantly increasing. This work aims to investigate the possibility of using recycled polyethylene terephthalate (PET), utilised as a partial substitute for fine aggregate, and waste glass, implemented as powder, serving as a partial substitute for cement in the manufacturing of the cementitious composites. An experimental study was carried out to evaluate the physical and mechanical properties of the resultant cementitious composites. The incorporated PET aggregate comprised 0%, 5%, and 10% by volume of silica sand and 0%, 10%, and 20% glass powder by weight of cement. The addition of waste raw materials augmented the flow of fresh mortars, predominantly subsequent to the introduction of PET recycle. The deployment of artificial aggregate in mortars induces a decrease in the volumetric density. Concurrently, the mechanical properties of mortars enriched with waste materials exhibited a reduction, in terms of both compressive and flexural strength, with the detriment escalating in conjunction with the content of waste raw materials. An analysis of statistical significance of effects, grounded in an analysis of variance, is delineated within this document, pinpointing the quantities of waste raw materials that can be assimilated in mortars without inducing a substantial deterioration of strength properties. Through studies on phase composition, it has been demonstrated that the utilised glass waste, possessing a grain size analogous to cement, exhibited poor pozzolanic properties. The test results indicate that it is possible to partially replace cement with glass powder, up to 10%, and fine aggregate with PET waste, up to 5%, without a significant reduction in the mechanical properties of the material.

Keywords: PET; waste glass; strength; waste disposal; cement mortar; pozzolanic activity



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1. Introduction

Plastics, synthetically produced materials, are ubiquitous across various economic sectors and facets of life owing to their distinctive properties, such as low density, high strength, commendable mechanical properties, and convenience in shaping and processing of the final products. The combination of economical production and high consumer demand has fuelled a consistent annual surge in plastic production. In 2021, global plastic production amounted to 390.7 million tonnes, with Europe contributing 57.2 million tonnes. This included plastics derived from non-renewable raw materials like thermoplastics, thermosets and PUR, post-consumer recycled plastics, and bio-based plastics, utilised in the fabrication of parts and products [1]. According to data from Conversio Market & Strategy GmbH (2021) [2], the packaging sector consumes approximately 44% of global plastic production, primarily deploying a diverse range of packaging materials including

PP, LDPE, LLDPE, HDPE, MDPE, PS, PET, and other thermoplastic polymers [1]. In 2021, PET production constituted about 6.2% of global and 5.3% of European plastic production, equating to approximately 24 million tonnes and 9.3 million tonnes, respectively [1].

The immense production volumes pose substantial management challenges, given that plastics are predominantly categorised as non-biodegradable, persisting in the environment for centuries. Accumulated unrecycled polymer waste threatens ecosystems and human health [3]. An eco-conscious approach focuses on mitigating environmental pollution through effective waste management strategies. Eurostat data indicates a 117% increase in plastic recycling and a 77% increase in incineration energy recovery between 2006 and 2020, with landfilling reduced by approximately 47%. Nonetheless, about 23% of post-consumer plastic waste still ends up in landfills. Plastic packaging recycling in the EU was at 37.6% in 2020, marking an 11.2% increase since 2006 but showing a 4.8% decrease compared to 2016, raising significant concerns [4].

Polymer recyclates have potential applications across various sectors including the construction industry, enhancing the rate of material recycling. Polymer wastes such as PET, PP, LDPE, EVA, PVC, ABS, SBS, and others are utilised, inter alia, to modify mineral and asphalt mixes to bolster their mechanical and operational parameters, like rutting resistance, strength, and viscoelastic and fatigue properties [5–7]. Thermoplastic elastomers enhance the binder's elastic properties and fatigue resistance, while plastomers enhance the stiffness and deformation resistance under load, prolonging the service life of asphalt pavements, especially those burdened with heavy traffic or situated in hot climates [8]. The granulation and type of polymer determine the efficiency of asphalt modification and dictate its functionality [9].

The literature posits the feasibility of employing polymer waste as a partial substitute for fine and coarse aggregate or as fibres for concrete reinforcement [10–13]. Waste PE, PP, and PET in forms like pellets or flakes can compromise the compressive strength of mortars, while enhancing the insulation and impact resistance and reducing the water vapour permeability [14]. The alteration in mechanical properties of concretes, using PET as a substitute for part of the fine aggregate, is contingent upon the dimensions, shape, and percentage of waste. Generally, an increase in PET percentage induces a decline in flexural and compressive strength, concrete density, and consistency [15]. The usage of PET, measuring between 5 and 15 mm and 2.6 and 11.4 mm, as a substitute for 25–75% and 10–20% of fine aggregate, respectively, led to a decline in the aforementioned properties [16,17]. Conversely, there are instances which report the enhanced strength of concrete with a 10% composition of PET, having a grain size of 2–4.9 mm and 0.05–2 mm [18]. Other authors have indicated that the optimum content of PET used as a fine and coarse aggregate is only 1% by volume or less [19,20]. PET coarse aggregate proves beneficial for structural concrete, enhancing the workability of concrete mixes with lower water to cement ratios, without a substantial compromise to mechanical properties [11]. Polymers like PP and PET, when used as reinforcing fibres, mitigate the occurrence of cracks during plastic shrinkage [21,22] and augment the flexural strength of cementitious composites. Studies by Banthia and Gupta reveal that finer and elongated PP fibres outperform the coarser and shorter ones in regulating the plastic shrinkage of concrete. Moreover, PET fibres in concrete minimise the prevalence of cracks and reduce its susceptibility to brittle fractures [23].

Glass stands as the predominantly used packaging material, producing waste volumes parallel to plastics. Eurostat data reveal that between 2009 and 2020, glass waste saw a 13.5% increase, amounting to 15.2 million tonnes, whereas plastic packaging waste rose by 26.7%, equalling 15.5 million tonnes during the same timespan [24]. The 2020 recycling rate for glass packaging was 76%, marking a 13.8% increase since 2006 [25]. Waste glass is remelted in smelting furnaces into glass mass, from which new products are formed.

Crushed into finer fractions, waste glass can serve as an ecological substitute for cement, aiding in the reduction of CO₂ emissions; the manufacturing of one tonne of cement yields 0.9 tonnes of CO₂ emissions. Various studies support the notion that substituting approximately 10–20% of cement with glass powder results in concrete possessing superior

strength compared to mixes devoid of this additive [26–28]. Employing glass in concrete as a supplementary cementitious material (SCM), without compromising its strength, mandates the meticulous selection of its quantity and granularity. Depending on several factors including the alkalinity of the pore solution, calcium content, and the particle size of the glass, the dissolved silica may repolymerise into an expansive ASR gel, form calcium silicate hydrate (C-S-H) phases, or yield both products [29]. It has been demonstrated that finely ground glass exhibits pozzolanic behaviour, with its pozzolanic properties diminishing as the particle size increases [27]. Conversely, when glass partially replaces fine or coarse aggregates, it exhibits alkali–silica reactions (ASR), necessitating the use of low alkaline cement and mineral additives to mitigate the risk of ASR occurrence [30,31]. Appropriately quantified glass dust in concrete can shield it from the detrimental reactions of aggregates with alkalis, displaying a resistance to chloride corrosion comparable to that of concrete incorporated with fly ash [32,33].

The imperative to recycle waste materials remains paramount, which, beyond its ecological dimension and commitment to environmental care, also bears significant economic rationality. To curtail the amount of waste sent to landfill, the European Union promulgated Directive 2018/852 established mandated thresholds for the recovery and recycling pertinent to the management of packaging and associated waste. According to this Directive, member states are obligated to recycle 65% of packaging waste by 2025; this includes 50% of plastics and 70% of glass [34].

Numerous studies presented at the EATA 2023 conference indicate a strong need to utilise plastomers, including PET, for the production of asphalt mixtures. The dry method, which involves introducing PET flakes into the recycled mixture, is used to build bounded road bases with a cement binder. In work [35], it was concluded that there is a lack of studies on the effects of the PET content on concrete behaviour. However, it was indicated that the possible optimal replacement of the aggregate by PET ratio is 1–5%. In turn in work [36], it has been suggested that replacing sand with waste PET particles positively affects the strength-related values of concrete specimens as long as the replacement ratio is less than 15%. Therefore, the application of PET as an aggregate substitute has environmental and practical meaning as well.

The objective of this research is to explore the feasibility of utilising waste from PET and glass packaging as an additive for cement mortar. Insights garnered from the literature review ascertain that PET can serve as a partial aggregate substitute and glass powder as a partial cement substitute. A discernible void is evident in both the national and international literature regarding the combined impacts of these additives on the properties of both fresh and hardened mortar. The ability to integrate both forms of waste materials would be advantageous, catering to both environmental and economic considerations and enhancing the recyclability of packaging waste.

2. Materials and Methods

2.1. Materials Characterization

2.1.1. Cement

Portland cement CEM I 42.5 R with a density of 3.10 g/cm³ and a chemical composition as shown in Table 1 was used as a binder for the slurry and mortar samples. The granulometric composition of the cement, determined by laser diffractometry (HELOS KR laser diffractometer), is shown in Figure 1 and Table 2.

Table 1. Chemical composition of cement.

Material	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	K ₂ O	Na ₂ O	Na ₂ O _e
Cement	18.96	5.19	2.77	62.03	1.60	3.15	0.84	0.21	0.76

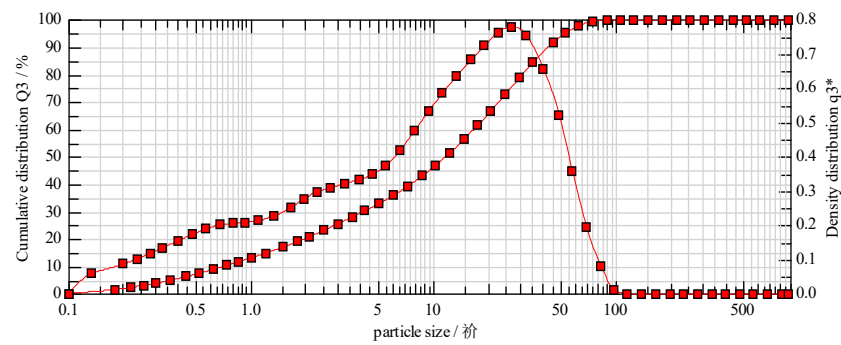


Figure 1. Granulometric composition of cement, q_3^* means q_{3lg} .

2.1.2. Waste Glass

The glass powder was procured through the mechanical crushing of glass jars, which were preliminary stripped of labels and adhesive residues, then washed and dried. Initially, the glass was crushed using a hand-held steel mortar before being processed in a RETSCH BB 50 jaw crusher until a fraction able to pass through a 0.063 mm mesh sieve was obtained (Figure 2). The granulometric composition of the ground glass, ascertained using the identical method utilised for determining the grain size of the cement, is illustrated in Figure 3 and Table 2.

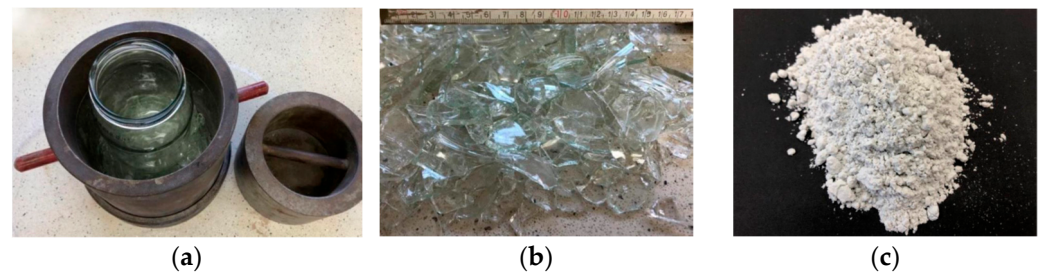


Figure 2. Glass powder preparation process: (a) pre-crushing of glass jars, (b) cullet, (c) glass powder.

Table 2. Granulometric characteristics of cement and glass powder.

Sample	$d_{10} / \mu\text{m}$	$d_{50} / \mu\text{m}$	$d_{90} / \mu\text{m}$
Cement	0.71	11.60	42.78
Glass powder	1.32	18.93	58.12

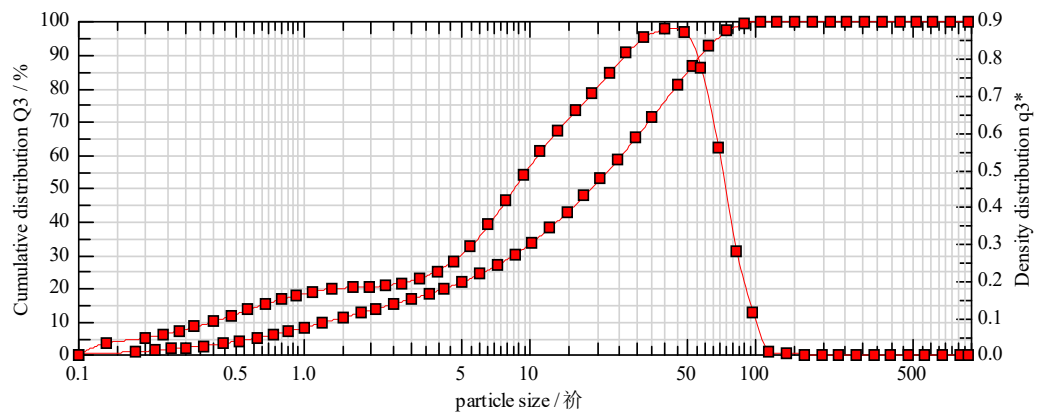


Figure 3. Granulometric composition of glass powder, q_3^* means q_{3lg} .

The grain composition analysis of glass powder, obtained through the grinding method, demonstrates that 90% of grains have a diameter less than 58.12 μm , while 50%

have a diameter of less than $18.93\ \mu\text{m}$. The results reveal that the grain size of the glass is larger than that of the cement used, where 90% of grains have a diameter less than $42.78\ \mu\text{m}$, and 50% have a diameter of less than $11.60\ \mu\text{m}$.

2.1.3. PET

Recycled PET waste from packaging was used as a partial substitute for fine aggregate (% by volume) in mortars. The density of PET was $1.38\ \text{g}/\text{cm}^3$. The preparation of the actual PET fractions commenced with the segregation of the material, namely, sieving through a 4 mm sieve with a mechanical shaker to obtain the 0–4 mm fraction (Figure 4). The results of 0–4 mm fraction sieve analysis are shown in Figure 5.

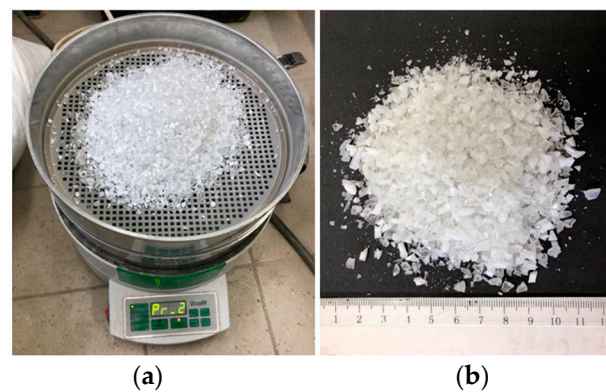


Figure 4. PET waste: (a) pre-separation of coarse fractions of PET waste on MULTISERW-Morek mechanical shaker; (b) PET of grain size 0–4 mm used for testing.

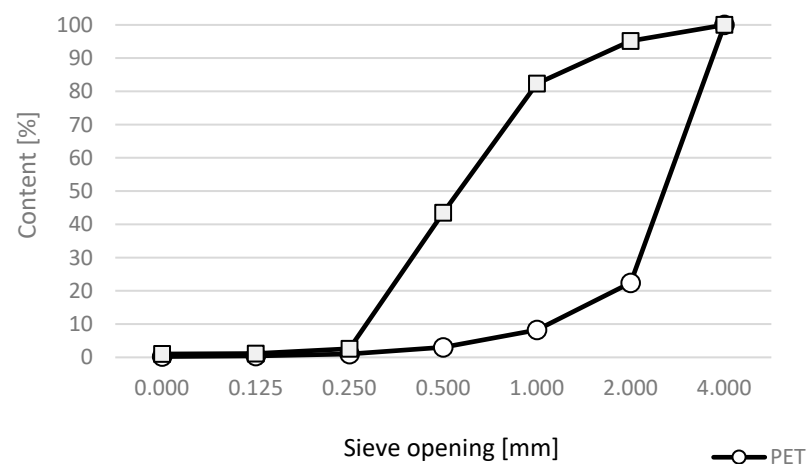


Figure 5. The grain size curves of the aggregates used; PET, industrial silica sand.

2.1.4. Silica Sand

Silica sand of 0–2 mm fraction was used for the mortars. The sand was washed and dried at $105\ ^\circ\text{C}$ in a laboratory dryer and filtered through a sieve. The results of sieve analysis are shown in Figure 5.

2.1.5. Water

Tap water meeting the requirements of EN 196-1 [37] was used for the mortars.

2.1.6. Mortar Mix Recipes

Mortar mix was prepared in accordance with EN 196-1 [37]. The w/c ratio was 0.5. Nine mixes were prepared, considering the following variables: the degree of substitution of sand by PET waste (5, 10% by volume) and the degree of substitution of cement by glass

powder (10, 20% by weight). The properties of the manufactured mortars were compared to those of a reference mortar without the addition of glass powder and plastic. Mix recipes [kg/m³] are shown in Table 3.

Table 3. Mortar mix recipes.

Mixture ID	Composition of Mortar Mixtures [kg/m ³]				
	Cement	Glass	River sand	PET	Water
0S-0PET	511.6	0.0	1534.8	0.0	255.8
10S-0PET	460.4	51.2	1524.1	0.0	255.8
20S-0PET	409.1	102.3	1513.4	0.0	255.7
0S-5PET	511.6	0.0	1458.0	40.0	255.8
10S-5PET	460.3	51.1	1447.3	40.0	255.7
20S-5PET	409.1	102.3	1436.6	40.0	255.7
0S-10PET	511.6	0.0	1381.3	79.9	255.8
10S-10PET	460.3	51.1	1370.9	79.9	255.7
20S-10PET	408.9	102.2	1360.5	79.9	255.6

2.2. Methods

Mortars were prepared in accordance with the provisions of EN 196-1 [37]. Three beams of 4 × 4 × 16 cm were moulded from each mix. The mortar was dispensed into moulds in two layers, each compacted with 60 shakes on an automatic vortex shaker. After 24 h, the hardened mortars were demoulded and submerged in water for 28 days and 56 days, respectively.

The volumetric density, consistency of fresh mortar (by flow table), and air content of the prepared fresh mortars were ascertained according to the methodologies outlined in EN 1015-6:2000 [38], EN 1015-3 [39], and EN 1015-7:2000 [40] standards. Flexural and compressive strength tests were conducted in compliance with the provisions of EN 196-1 [37]. The determination of flexural strength was executed using the three-point loading method, where the load was conveyed to the opposite surface of the beam via a load roller. Compressive strength was examined on the lateral surfaces of the specimens, specifically for each of the 6 halves of the mortar beams procured from the flexural strength test. The load was administered to the lateral surfaces of the individual specimens, uniformly at a speed of 2400 N/s, using a CONTROLS C250kN press.

The impact of glass powder on the phase transformations in the slurries where cement was substituted by 10% and 20% by weight was also investigated. The *w/c* ratio was 0.5. The reference sample was cement slurry without glass powder. The slurries were preserved in individual plastic string bags. Post 24 h, an equivalent quantity of distilled water was introduced to each slurry to secure the appropriate maturing conditions.

Phase transformations were investigated over a span of 7–56 days through X-ray diffractometry. A PANalytical Empyrean diffractometer with Cu anode was used for this purpose. The scans covered an angular range of 5 to 65° 2θ, using a step size of 0.02 2 Th°. For the diffractogram analysis, the ICDD PDF-2 database was used [41].

3. Results

3.1. Density and Consistency

The results of tests on the influence of waste raw materials on the density, workability, and air content of the mixes are shown in Table 4.

Table 4. Results of fresh mortar properties.

Mixture ID	Results		
	Density [kg/m ³]	Air Content [%]	Flow [mm]
0S-0PET	2210	4.00	153
10S-0PET	2198	4.05	155
20S-0PET	2201	3.50	159
0S-5PET	2169	4.30	162
10S-5PET	2173	3.60	164
20S-5PET	2155	4.00	170
0S-10PET	2129	4.50	174
10S-10PET	2129	4.00	171
20S-10PET	2133	3.40	174

The density of fresh mortar mixes remains unaltered with an increase in the proportion of glass powder, partially substituting cement in the mortars. The reduction in the density of PET mortars is attributed to the substitution of some of the sand with waste aggregate, likely due to the lower density of PET compared to silica sand. The combined utilisation of waste raw materials results in a decrease in the density of mortars fabricated from them compared to a sample without additives. The flow of mortar mixes experiences a minor increase with a rise in the glass powder content and a more substantial increase with a rise in the PET proportion. PET waste, utilised as a 5–10% replacement for fine aggregate, comprises approximately 80% of 2–4 mm particles, distinctly diverging from the grain size of silica sand. Owing to the decrease in the specific surface area of the entire aggregate pile, an augmentation in the flow of mortars constructed with a polymer aggregate is observed. Concurrently, the employment of both waste raw materials culminates in the recorded elevated mortar flows. The air content was the lowest in mortars with 20% glass content and the highest in the case of 10% PET content. Mortars with 10% glass content had comparable air contents to mortars without glass powder.

3.2. Flexural Strength

The flexural strengths, influenced by the proportion of glass powder, waste PET, and their combination, ascertained after 28 and 56 days of curing are illustrated in Figure 6a,b. Both glass powder and PET diminish the flexural strength of mortars; the effect is most pronounced for the highest concurrent content of glass powder and 5 and 10% PET content. The employment of PET recycle and glass powder independently diminishes the flexural strength of the mortars comparably (tests after 28 days of curing).

3.3. Compressive Strength

Figure 7a,b show the results of compressive strength tests depending on the content of waste glass and PET.

Regardless of the type of waste material incorporated, the compressive strength of mortars diminished after 28 days of curing, with the most significant decreases in strength exhibited by mortars where 20% glass powder content partially replaced the cement. This is likely attributable to the limited capacity of the powder to react with $\text{Ca}(\text{OH})_2$ within the given timeframe. The decline in strength of mortars, where 10% of the binder is substituted by powder, is 11%, while the introduction of 20% powder results in a 25% decrease in strength. This augmented reduction in the strength parameter could be associated with the agglomeration of powder particles within the slurry matrix. The incorporation of PET ameliorates the adverse effects of glass powder on strength. After 56 days of maturation, the strength of mortars with 20% glass powder content and those with a combination of 20% glass powder and 10% PET content, exhibited augmentation in comparison to the values noted after 28 days. The strength values of the PET mortars after 28 and 56 days exhibited similar characteristics.

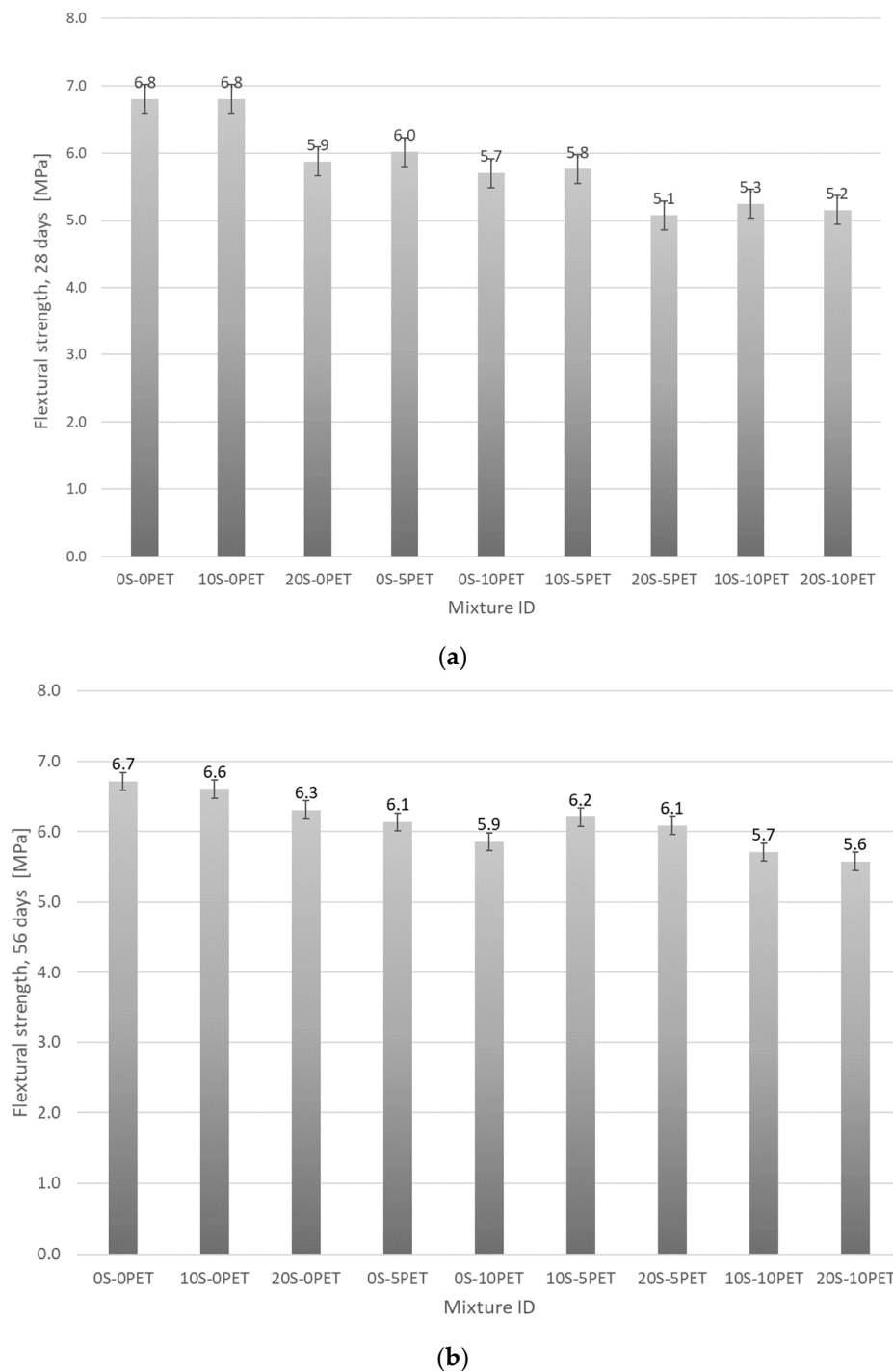
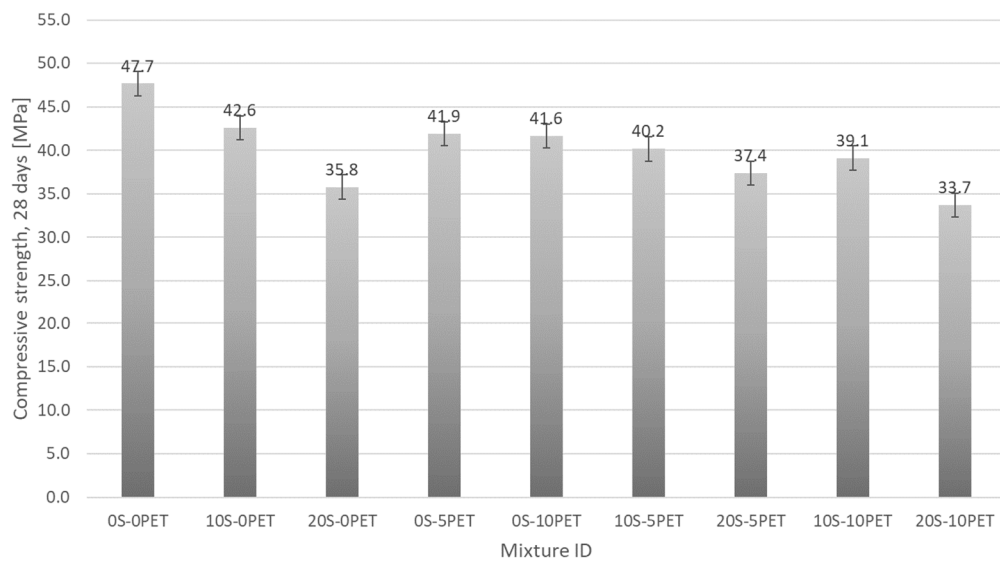
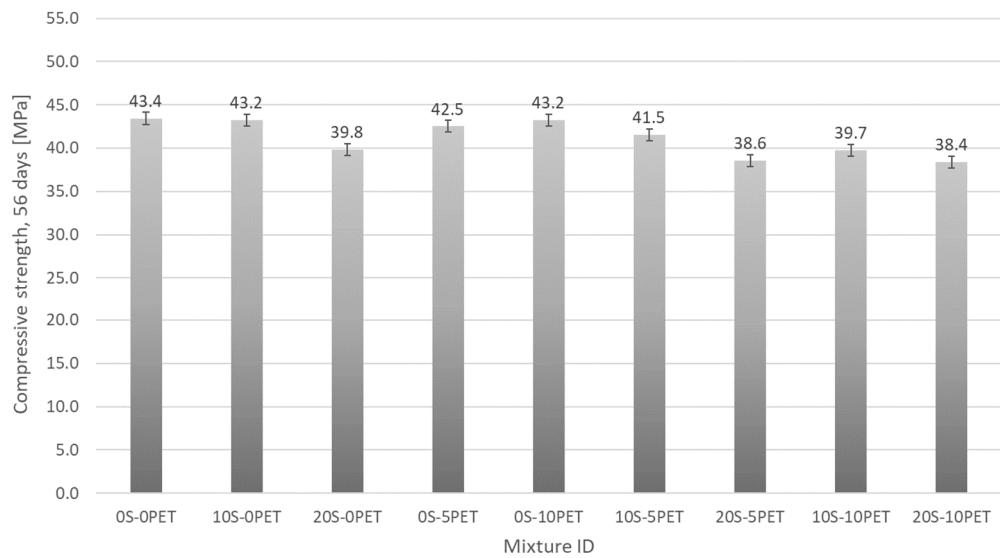


Figure 6. Flexural strength of mortars after (a) 28 days of curing and (b) 56 days of curing.

A visual examination of the mortar samples subjected to mechanical testing revealed a weakened interaction zone between the polymer aggregate grains and the cement slurry (Figure 8). This aspect could be a contributing factor to the decreased flexural and compressive strengths of the tested composites embedded with recycled materials. The weak bond between the PET aggregate and the cement matrix is the main problem of combining the two materials. Unlike the natural aggregate, the smooth and hydrophobic surface of polyethylene terephthalate impedes the optimal binder hydration around the grains and hampers the formation of a sufficiently durable bond between the two materials.

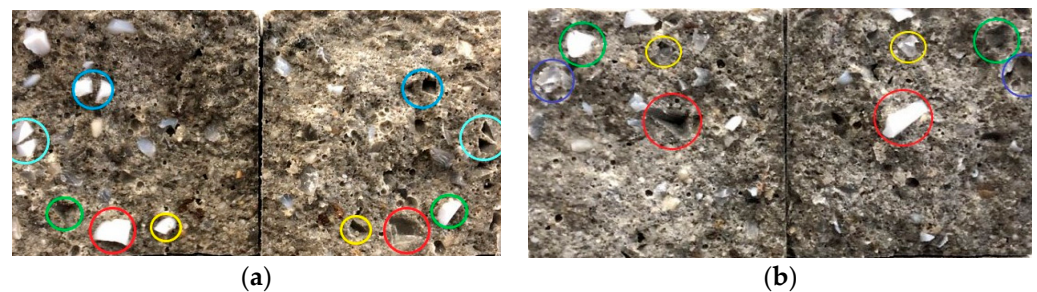


(a)



(b)

Figure 7. Compressive strength of mortars after (a) 28 days of curing and (b) 56 days of curing.



(a)

(b)

Figure 8. Fracture images of mortar samples after flexural strength testing: (a) 0S-10PET, (b) 20S-5PET. The circles show where the PET grains were torn out.

3.4. Phase Transformation

The phase transformations of slurries without glass powder and with 10% and 20% glass powder as a binder component were analysed over 7, 28, and 56 days of hydration using X-ray diffractometry. The results of the analyses are shown in Figure 9a,b.

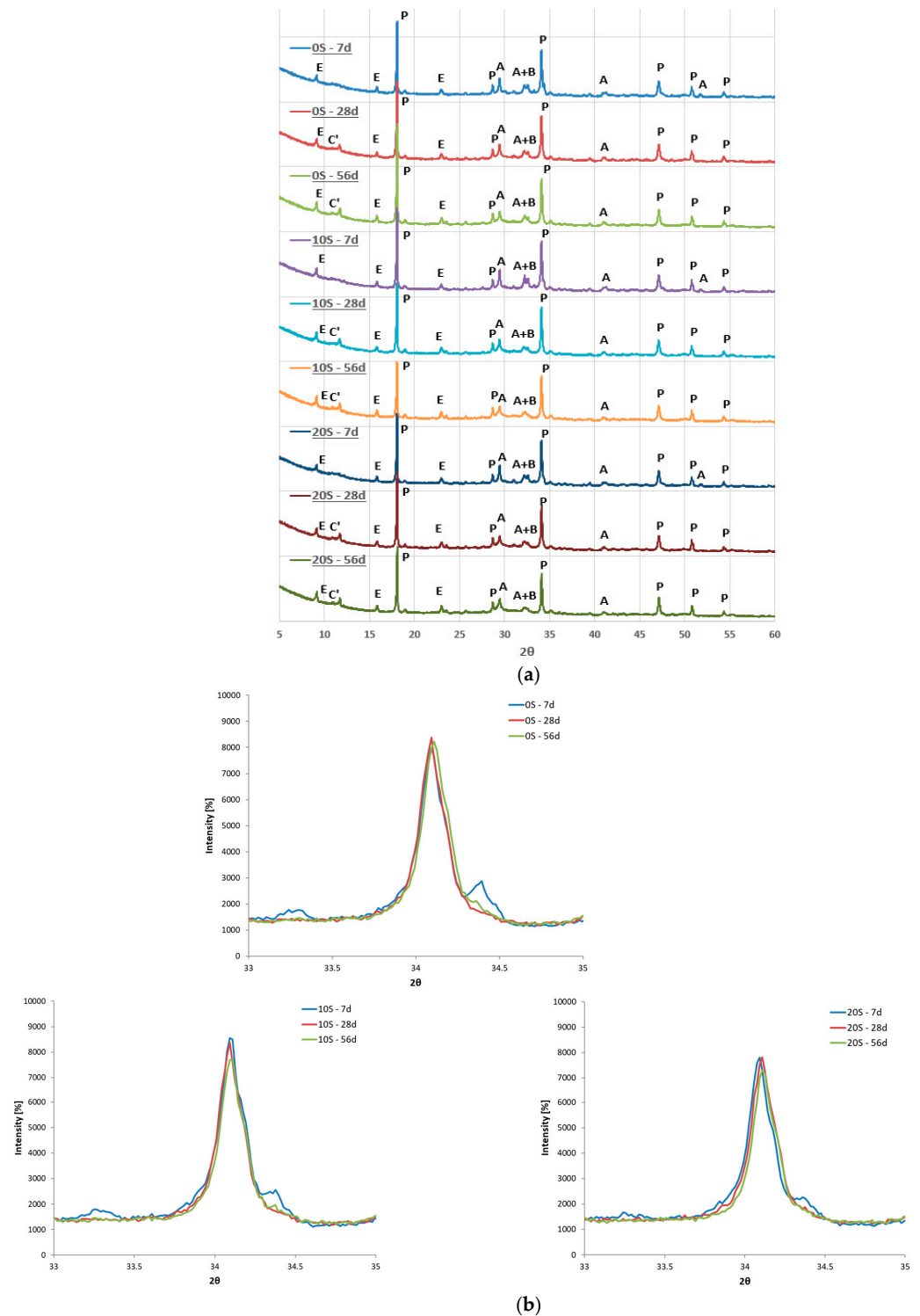


Figure 9. Analysis of phase transformations of slurries with 0%, 10%, and 20% glass powder content; (a) summary of diffractograms of cement slurries after 7, 28, and 56 days of hydration. Explanation of abbreviations: A—alite; A + B—alite and belite reflections; E—ettringite; P—portlandite; C'—C-S-H; (b) changes in portlandite reflection intensity (angle $34^\circ 2\theta$) as a function of time.

The phase composition of cement slurries with glass powder does not diverge from that of reference slurries. However, differences were observed in the intensity of the reflections, signalling the presence of individual phases (Figure 9a). As hydration processes unfold, the intensity of the reflections from alite and belite diminishes, while portlandite and the C-S-H phase materialise as hydration products. In slurries where part of the cement has been supplanted by glass powder, the intensity of the alite phase is inferior to that of the reference slurries, attributable to the diminished content of alite in the slurries where the binder is an amalgamation of cement and glass powder. Contrary to anticipation, elevated reflections from the portlandite were identified in the slurries with 10% glass powder compared to those where cement constituted 100% of the binder, with the intensity of these reflections decreasing over time (Figure 9b). In slurries with a 20% glass content, the portlandite reflection intensities were analogous to those documented in the reference sample. The noted decline in portlandite intensity over a period of 28–56 days denotes that the glass interacts with the portlandite, substantiating its pozzolanic properties. However, the nominal decreases in $\text{Ca}(\text{OH})_2$ intensity at approximately $34^\circ 2\theta$ suggest exceedingly poor pozzolanic properties of the glass under investigation.

3.5. Analysis of Significance of Effects

The analysis of effects was performed based on a multivariate analysis of variance. The analysis of variance was performed based on the classic linear model in the same way as in the single classification [42]. One of its results was the determination of the MSE error (mean square error) required to determine the subsequent contrasts and determine the random effect of the experiment (repeatability). The aforementioned analysis of effects was conducted based on a multifactor analysis of variance. The primary objective of such analysis was to determine the magnitude of the effects and to delineate contrasts amongst the array of combinations of the shovel amount and the PET additive in the concluded experiment. Initially, a verification of the assumptions of the analysis of variance was conducted. Consequently, preliminary normality tests were executed on the dependent variables: compressive strength after 28 and 56 days of curing and flexural strength after 28 and 56 days of mortar curing. The presence of outliers was also examined according to the Grubbs test procedure [42]. No outliers were identified within the analysed set. Additionally, all dependent variables for the Shapiro–Wilk test achieved a p -value > 0.05 , providing no basis to reject the null hypothesis, which posits that the probability distribution of the results of the dependent variables conforms to a normal distribution. Upon satisfying the fundamental assumptions of the analysis of variance, its linear form, incorporating interaction components (cross-validation analysis), was used. In Table 5, the results of parameter significance are separately illustrated for each identified variable at a significance level of $\alpha = 0.05$.

Table 5. ANOVA results for individual characteristics (effective hypothesis decomposition).

	Flexural Strength after 28 days [MPa] (p -Value)	Compressive Strength after 28 days [MPa] (p -Value)	Flexural Strength after 56 days [MPa] (p -Value)	Compressive Strength after 56 days [MPa] (p -Value)
Glass content [%]	0.0009 *	1.3199×10^{-8} *	0.2674 *	2.41558×10^{-5} *
PET content [%]	1.68×10^{-5} *	0.0004 *	0.0001 *	0.0335 *
Glass content [%] $\times$ PET content [%]	0.4477	0.0952	0.8944	0.2194

*—significant effect.

It is imperative to note that for all categories of mortar properties (dependent variables), both the quantity of glass and the amount of PET significantly impacted the variation in compressive and flexural strength after 28 and 56 days of the curing process of the mortar samples. Moreover, a multifactor effect size analysis was executed using the Shapiro–Wilk test. This analysis was conducted to ascertain the magnitude of the impact and to determine

the level of explanation of the variability in the cumulative set of outcomes attributed to the dependent characteristics by the quantity of PET and glass. As a result, partial η^2 was used, which is the quotient of the sum of squares attributed to the effect relative to the sum of squares of the given effect and the sum of ANOVA error squares [43]. As a result, the addition of glass explained 69% of the variation in the dependent variables studied, while the amount of PET explained 63% of their variation overall. Regarding the interaction between the quantities of PET and glass, the degree to which the variation in dependent characteristics is explained is merely 27%. Therefore, both dependent variables (the quantity of glass and the quantity of PET) elucidate the examined compressive and flexural strengths to a comparable degree. When evaluating the effects, it is sensible to illustrate the distribution of weighted means computed during the implementation of the ANOVA method algorithms. The results have been categorised according to the type of characteristic under investigation and are depicted in Figure 10.

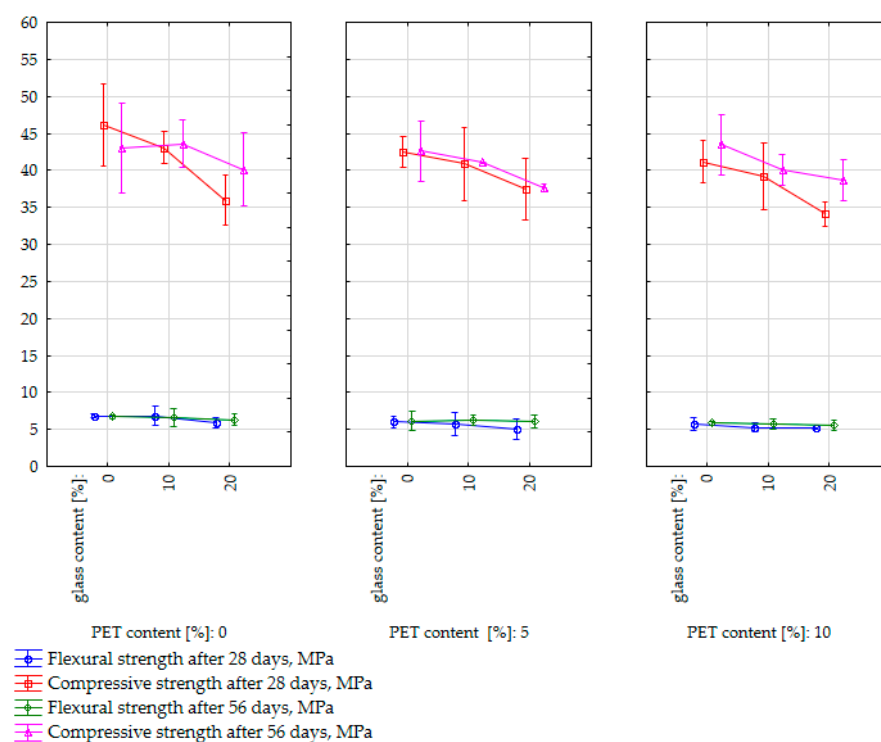


Figure 10. Interaction diagram of the weighted means of the studied characteristics.

As presented in Figure 10, a marginal difference can be discerned between the compressive strength results after 28 days and 56 days of mortar curing. Furthermore, a discernible declining trend in compressive strength was noticed irrespective of the curing duration. By scrutinising the error bars, it is not feasible to definitively deduce for which quantities of PET and glass the alteration in the value of the dependent characteristics is or is not significant. This is consequential considering the potential recycling of PET polymer and glass waste.

The search for contrasts was performed using the Tukey test, elaborated in the 1950s. It resulted from some discrepancies in the procedure described by Fisher concerning a least significant difference procedure. A significant difference of the Tukey to Fisher's test is the equal probability of committing a type I error, independent of the number of comparisons, which does not exceed the assumed level of significance in accordance with Formula (1):

$$HSD = q_{\alpha,k,N-k} \sqrt{\frac{MSE}{n}} \quad (1)$$

where *HSD* is the honestly significant difference, $q_{\alpha,k,N-k}$ is the tabulated quantile of the standardised range distribution, *MSE* is the mean square error, *N* is the total samples number, and *n* is the sample number in the group. As a result, any difference between two groups greater than the *HSD* is considered a significant pair. The list of relevant groups is determined iteratively by searching through all combinations. Therefore, the number of similarities varies depending on the nature of the research object under study (its repeatability). This Tukey test can be performed for any confidence interval, which was set at 0.05 in the research.

The groundwork for distinguishing contrasts between the average scores allotted to each combination of PET and glass quantities is furnished by an analysis of variance. This indicates the existence, at the very least, of a significant pair between the average scores for the instances (Table 3). To achieve this, a conservative Tukey's test (post hoc) was used [44]. For its application, preliminary Bartlett's tests of variance homogeneity were conducted. The outcome of the test manifested that there was no ground to assert that the variability of the results differed amongst the case groups. The findings are delineated in the subsequent Tables 6–9.

Table 6. Tukey's test for variable compressive strength after 28 days.

Glass Content [%]	PET Content, [%]	Compressive Strength after 28 days [MPa] (Mean)	1	2	3	4	5
20	10	34.09			****		
20	0	35.95			****	****	
20	5	37.45		****	****	****	
10	10	39.23	****	****		****	
10	5	40.91	****	****			
0	10	41.18	****	****			
0	5	42.5	****				****
10	0	43.07	****				****
0	0	46.1					****

Homogeneous groups are identified by the symbol “****”.

Table 7. Tukey's test for variable compressive strength after 56 days.

Glass Content [%]	PET Content, [%]	Compressive Strength after 56 days [MPa] (Mean)	1	2	3
20	5	37.6		****	
20	10	38.62		****	****
20	0	40.09	****	****	****
10	10	40.1	****	****	****
10	5	41.03	****	****	****
0	5	42.6	****		****
0	0	43.03	****		
0	10	43.5	****		
10	0	43.61	****		

Homogeneous groups are identified by the symbol “****”.

Table 8. Tukey's test for the flexural strength variable after 28 days.

Glass Content [%]	PET Content, [%]	Flexural Strength after 28 days [MPa] (Mean)	1	2
20	5	5.08	****	
20	10	5.15	****	
10	10	5.25	****	
0	10	5.73	****	
10	5	5.76	****	****
20	0	5.88	****	****
0	5	6.02	****	****

Table 8. *Cont.*

Glass Content [%]	PET Content, [%]	Flexural Strength after 28 days [MPa] (Mean)	1	2
0	0	6.81		****
10	0	6.81		****

Homogeneous groups are identified by the symbol “****”.

Table 9. Tukey’s test for the flexural strength variable after 56 days.

Glass Content [%]	PET Content, [%]	Flexural Strength after 56 days [MPa] (Mean)	1	2	3
20	10	5.58	****		
10	10	5.71	****	****	
0	10	5.86	****	****	****
20	5	6.086667	****	****	****
0	5	6.14	****	****	****
10	5	6.21	****	****	****
20	0	6.31	****	****	****
10	0	6.6		****	****
0	0	6.71			****

Homogeneous groups are identified by the symbol “****”.

Reviewing the data in Table 6, it is notable that the incorporation of up to 10% glass and up to 5% PET does not induce a substantial change (reduction) in the compressive strength of the mortar after 28 days, compared to the reference mortar. The most significant decline in compressive strength after 28 days was observed when glass was incorporated at 20%, irrespective of the quantity of PET added. The subsequent impact of the additives on the mortar strength over time is evident in the comparisons made for the compressive strength characteristic after 56 days (Table 7).

It is worth noting that the group of results represented by the reference mortar is marked by number 1. It should be stated that when dosing separately, PET up to 10% and glass up to 10% do not result in a significant difference in compressive strength results after 56 days of curing compared to the reference mortar (without additives). This conclusion follows from the juxtaposition of the similarities of fuzzy sets 1 and 2. Observing the extent of variation in the mean strength (Table 7) after 56 days of curing and the number of similarities within the groups compared to the compressive strength after 28 days, it should be concluded that there is a deceleration in the dynamics of compressive strength increase over time. The simultaneous use of glass and PET, especially at 20% glass content, results in a significant reduction in strength after 56 days of maturation. The results of the analyses show that replacing cement with glass powder reduces the compressive strength of the mortars to a greater extent than PET aggregate used as a partial substitute for fine aggregate.

Another important group of mortar properties is flexural strength. First, a multiple comparison analysis was carried out for the flexural strength results after 28 days of mortar curing (Table 8).

Analysing the fuzzy state of the Group 1 and Group 2 sets, it should be noted that only dosing with 10% glass does not result in a significant difference in the flexural strength result after 56 days compared to the reference mortar. By increasing the amount of PET to 5% and glass to 20%, the flexural strength results after 28 days are still non-significantly different compared to the result of the reference mortar (Group 1), but the presence of the same cases in the second group (Group 2) does not yield a certain conclusion about the variation in the set of the given characteristic. The final characteristic was the flexural strength after 56 days of curing (Table 9).

The results shown in Table 7 indicate that only 10% of the added glass does not induce a significant variation from the reference mix. In contrast, dosing as little as 20% glass and

10% PET additive results in a significant decrease in the flexural strength after 56 days of maturation compared to other combinations of glass and PET additives. Thus, as in the previous analysis, a content of 10% is an acceptable limit for the addition of glass that does not impair the flexural strength properties of the mortar.

4. Discussion

The presented results show the influence of waste raw materials on the physical and mechanical properties of cement mortars made with them. No research has been carried out on the simultaneous influence of glass powder and PET on the properties of cement composites, both in Poland and worldwide. The obtained research results allowed for the assessment of the possibility of using these materials in cement composites, and in the future, they may help in developing the technical possibilities of introducing these materials in the building industry. The use of packaging waste can contribute to the development of sustainable production of composite materials, effective waste management, and environmental protection.

Both glass powder and PET increased the liquidity of the mortar mixes. Different observations of the effect of PET on workability are cited in the literature. As the volumetric proportion of PET increases as a fine aggregate, a deterioration in workability was observed [45], while others have indicated an increase in the flow of mixes with PET [46]. Similar discrepancies have been indicated with the use of PET fibres [12,47]. PET can lead to the disruption of the structure of mortars and concretes, resulting in a reduction in the flow of mixes. The discrepancies may be due to the fact that the flow of mortar mixes and concretes made with PET depends on, *inter alia*, the shape, grain size, texture, specific surface area of the artificial aggregate used, and the w/c ratio. Safi et al. indicated that plastic waste can be used for self-compacting mortars and concretes, where the mixtures must have good flow [46]. Plastic particles, due to their smoother surface than sand, do not absorb water, therefore the excess water improves the workability of mixtures.

PET reduces the density of mortar mixes with its addition; the reason for this being the lower relative density of artificial aggregate (specific gravity) compared to natural aggregate [15]. The density of the mix with 10% PET decreased by approximately 4%. There were no significant differences between the air content in mixtures with and without waste raw materials; however, PET increases the air content in the mixtures. This is probably due to the voids formed between the PET aggregate and the cement slurry, which results in air being trapped close to the surface of the hydrophobic aggregate [48,49].

PET decreases the compressive and flexural strengths of the mortars made, with the recorded decreases in strength showing no significant differences from the reference mortars when PET was introduced at 5% by volume. The increased number of weakened zones in the mortar matrix is responsible for the decreases in compressive strength of mortars with PET volumetric addition. The weakening of the contact zone between the PET aggregate and the cement slurry is due to the weak bond between the cement matrix and the hydrophobic surface of the plastic. As Safi et al. indicated, the plastic waste–binder interface is less dense with cracks and poor adhesion between these two materials [46]. When mortars were tested in compression, whole particles of artificial aggregate were pulled out, as also indicated by Al-Manaseer and Dalal in their study [50]. The contact zone between the polymer aggregate and the cement slurry is weaker than the contact zone between the slurry and a mineral aggregate. Interestingly, the decreases in compressive strength of mortars with 5% and 10% by volume of PET are similar and statistically insignificant at around 12–13%. The particle shape of the polymer aggregate is irregular, and the grains are larger than those of silica sand, which can play a significant role in determining the strength parameters. Thorneycross et al. replaced 10% of the sand volume with plastic waste and found no deterioration in concrete strength [51]. The authors similarly substituted 10% by volume of fine aggregate, as in the present paper. The difference, however, was in the grain size of the PET, which corresponded to the grain size of the sand being replaced. The use of 10% by volume of PET with a grain size of 2–4 mm resulted in only an approx. 4%

decrease in strength, while PET with a grain size identical to sand resulted in no decrease in compressive strength but as much as a 25% increase in flexural strength [51]. It can therefore be assumed that an appropriate adjustment of the grain size of the artificial aggregate will influence its applicability, without compromising the mechanical characteristics of concrete. In contrast, the inclusion of 10% of PET reduced the flexural strength of the mortars made, while at 5%, the decreases in value compared to the reference sample were not statistically significant. Also, the literature data indicate that PET applied in small quantities does not affect the flexural strength values obtained, and in some cases, this parameter is improved [45,47].

Glass powder used as part of the binder slightly increased the flow of the mortars. Glass has hydrophobic properties, thus more water is available at the same w/c ratio compared to the reference mortar, and thus, a better workability is observed [52]. In contrast, this effect is not as strong as mixes with PET. Also, the lower relative density of glass relative to cement can reduce the weight and density of the fresh mortars made, while the decreases in volumetric density of mortars with glass powder were insignificant in the systems analysed. It was indicated that the partial replacement of the cement mass with larger amounts of glass powder, reduces the air content in the mixture. In turn, the data of Garcia del Toro et al. indicated an increase in the degree of air entrainment of the concrete mixture with an increase in the glass content. They explained this phenomenon as the retention of the air bubbles by the surface energy of the glass being greater the finer the glass grains are [53]. However, Seong Kyum et al. found a decrease in air content in concrete mixtures made with waste LCD glass [54]. The formation of this feature most likely depends on the specific surface area of glass powder.

Decreases in the strength of mortars in which part of the cement has been replaced by glass powder have been noted—the higher the glass powder content, the lower the compressive strength values. The use of 10% by weight of glass powder in the binder results in an 11% reduction in strength, while 20% of glass powder results in a 25% reduction in strength. The results of the phase composition tests show that the glass powder exhibits very poor pozzolanic properties. The literature indicates that glass powder with a grain size of less than 150 μm should have good pozzolanic properties and be a partial replacement for cement [55]. Although the glass was ground to dimensions below 63 μm in the present study, satisfactory results were not obtained. Mayer, on the other hand, pointed out that the pozzolanic properties of glass powder were only in powder with a grain size below 45 μm [56]. In addition, the reaction of glass with portlandite, a product of cement hydration, should produce a C-S-H phase that seals the structure and increases the strength of the composite material. It is likely that a greater fineness of the glass powder would improve its reaction with $\text{Ca}(\text{OH})_2$ [57]. However, it can be assumed that glass powder of the grain size used in the study acts as a filler and, when used up to 10%, does not significantly reduce the flexural and compressive strength of the mortars. The lower strengths of mortars with glass as a binder component are also due to the lower cement content, and glass does not adversely affect the hydration processes. No increase in the strength of mortars with the simultaneous use of PET and glass powder was observed, where it was expected that the aggregate–slurry contact zone would be strengthened by the reaction with $\text{Ca}(\text{OH})_2$. Minimising the negative impact of fine waste PET aggregate on the strength of concrete was reported by Meena et al. [58], using silica dust as part of the binder. It should be noted, however, that silica dust exhibits very good pozzolanic properties, and hence, the higher strength values were recorded over time in relation to concretes without it.

5. Conclusions

The results of the tests and analysis allow the following conclusions to be drawn:

- The development of compressive and flexural strengths of mortars made with the addition of waste materials, i.e., glass powder and PET, is identical to the development of strength parameters for reference mortars made from Portland cement and silica

sand, while the strength values of mortars after the introduction of waste materials are reduced.

- The use of glass powder as part of the binder results in greater decreases in the strength of the mortars made than the partial replacement of the sand volume with PET waste.
- Glass used in an amount of up to 10% by weight of cement does not result in a significant decrease in the compressive and flexural strength, indicating that it can be used as a substitute for cement without compromising the aforementioned characteristics. The glass powder used, despite a fineness of less than 0.063 mm, shows very poor pozzolanic properties.
- PET waste of up to 5% does not significantly reduce the compressive and flexural strength of the mortars made. The contact zone between the PET aggregate and the cement slurry is weakened, which affects the lower strength values recorded.
- In the systems under consideration, the combined use of PET and glass powder is least favourable due to the deterioration in compressive and flexural strength, while the benefit of their use is associated with an improvement in the consistency of the mortar mixes made and a reduction in bulk density without an increase in the degree of aeration. Therefore, the suitability of mixes with waste for the production of concrete with an increased fluidity and reduced mass can be considered. Due to the lower density of PET compared to silica sand, PET aggregate can be used as a lightweight fine aggregate.

The results obtained and the literature study support the hypothesis that grinding the glass below a grain size of 0.063 mm can improve its pozzolanic properties. However, research should be undertaken into the influence of surface-textured PET on the formation of the synthetic aggregate–cement slurry contact zone. Research in this direction can contribute to increasing the disposal of packaging waste without significantly compromising the mechanical properties of mortars and concretes made from it. The authors shall consider adjusting the grain size of the synthetic aggregate to match the grain size of the natural aggregate being replaced in further studies.

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