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USE OF WASTE PRODUCTS IN THE FORM OF DUST AND GLASS FLOUR IN MORTARS

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ABSTRACT: The development of eco-innovation in the construction materials industry plays a key role in promoting sustainable development. Faced with dwindling natural resources, construction material manufacturers are increasingly turning to solutions that reduce their negative impact on the environment while ensuring high product quality. The aim of the study was to assess the possibility of using waste soda-lime-silicate glass as a reactive pozzolanic additive for cement mortars or as a non-reactive filler. The research involved the preparation of a series of mortars with different degrees of cement replacement with glass dust (10%, 20%, 30%) and a series with sand replaced with glass powder (20%, 35%, 50%). The setting time, bulk density, consistency, compressive and flexural strength, water absorption and capillary rise, as well as the microstructure of the mortars, were examined. When glass powder was used as a cement substitute, the decrease in compressive strength ranged from 8.5 to 16%, and the decrease in flexural strength from 6 to 9%. Ground glass in powder form did not exhibit full pozzolanic properties.

KEYWORDS: additive, glass, compressive strength, absorbability, capillary rise

Introduction

Nowadays, mankind is increasingly faced with limits on the natural resources needed to produce building materials. This is why eco-innovation in this field has become particularly necessary, as it allows producers of building materials to grow while protecting the environment. Eco-innovations play a key role in construction, as they help reduce the industry's negative impact on the environment. The implementation of modern ecological solutions allows for the reduction of natural resource consumption, minimisation of pollutant emissions and reduction of waste generated during the construction and operation of buildings.

Data indicates that cement production in Poland remains high, exceeding 18 million tonnes per year, with additional imports from other countries amounting to approximately 1 million tonnes. This means that total cement consumption is around 19 million tonnes per year. Such quantities are indicative of intensive construction activity and a significant impact on the environment and the economy. Today, cement is the second most consumed raw material in the world, after drinking water (Błaszczyński&Król, 2016). Increasingly, CEM IV pozzolanic cements and CEM V multi-component cements are beginning to appear in the offerings of cement plants (Mazurowski, 2007). Low-clinker cements are also favoured by the PN-EN 197-5:2021standard, which allows the production of CEM II/C multi-component Portland cement, with a clinker content in the range of 50-64%, and CEM VI multi-component cements, with a clinker content in the range of 35-49% (Giergiczny&Szybilski, 2014;Wierzbowska-Kujda, 2024). Non-clinker cement components have been used for many decades in the cement industry, and sufficient knowledge has been accumulated about their composition, effects on cement hydration and properties of hardened concrete. In view of the changing demand and supply conditions, it will also be necessary to analyse the hitherto little-researched waste materials. Research centres have been investigating the possibility of replacing cement with other materials, such as waste materials, for years. A natural choice of material for research is various types of glass, which is an ideal secondary material. It is an inorganic amorphous material, formed by rapidly cooling a liquid to a solid form, preventing crystallisation. The internal structure of glass is distinguished by the absence of the long-range ordering characteristic of crystals or polycrystals. There is only local ordering in the internal structure, on an atomic scale, as a result of which the structure of glass shows features common to that of an overcooled liquid, while at the same time exhibiting the mechanical properties of a solid, which by definition makes it an amorphous body (Gawlicki et al., 2013).

An overview of the literature

In Poland, we collect about 750 000 tonnes of glass every year. Despite growing environmental awareness, only 50-60 per cent of glass packaging is recycled.

The most common type of glass is conventional soda-lime-silicate glass. The basic raw materials used in its production are: quartz sand (SiO_2), in the amount of 68÷74%, which constitutes the glass body; limestone meal ($CaCO_3$), as an ingredient stabilising and hardening the glass, as well as increasing its chemical resistance, in the amount of 7÷14%; and soda ash (Na_2CO_3), lowering the melting point of the mixture, in the amount of 12÷16%. In addition to the main components, the following are added: aluminium and magnesium, increasing chemical and mechanical resistance, arsenic oxides, antimony and fluorine compounds, facilitating glass clarification and cullet, and accelerating the mixture's melting. In addition to sodium-calcium-silicate glass, a distinction can be made between boron-silicate glass, lead glass, optical glass, sodium glass or sodium-potassium glass refined with barium (Gawlicki et al., 2013; Biernacki et al., 2017;Gołek et al., 2020). Glass is an isotropic material. It has equal properties in every direction. It is a perfectly elastic material. It is also not subject to permanent deformation, but at the same time is characterised by brittleness when subjected to external forces. Glass has a high compressive strength of 500 - 1000 MPa. It is also resistant to the adverse effects of chemicals. This resistance depends, among other things, on the chemical composition of the glass, the condition of its surface, temperature and even the duration of exposure to selected external factors. A very important parameter of this material, as a building material component, is its chemical resistance to water (Gawlicki et al., 2013; Biernacki et al., 2017; Kylili&Fokaides, 2017).In the construction industry, waste glass may find application in the production of insulation and acoustic materials, as well as decorative elements.

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Previous studies have mainly focused on the use of crushed glass as a partial replacement for cement and/or aggregate (Drzymała et al., 2020; Kamali&Ghahremaninezhad, 2015; Małek et al., 2020; Olofinnade et al., 2018; Sikora et al., 2015). The results of these studies (Meena et al., 2018) indicate that the greatest increase in compressive and flexural strength is achieved when 15% glass powder is added. In addition, the introduction of ground glass into the concrete mix reduces the water absorption and porosity of the concrete (Omran et al., 2017). Concrete with cement replaced by 15% and 30% glass powder showed the greatest increase in strength and reduced porosity (Du& Tan, 2017). Other studies (Tamanna & Tuladhar, 2020) suggest that recycled glass powder (RGP) can be used as a cement substitute at a replacement level of up to 10%. Glass cullet is also used in the production of new products, such as glass fibres (Sordoń-Kulibaba, 2008). Considering that most studies focus on its use in concrete, we decided to analyse the possibilities of using glass cullet in cement mortars.

In mortar technology, waste glass can be used as a non-reactive filler or a reactive pozzolanic additive. The use of waste glass in mortar production depends mainly on the grain size of the ground glass and its reactivity. Glass grain sizes up to 0.3 mm show pozzolanic properties. It is then a potential replacement for cement. This is also confirmed in a study by Gołek et al. (2020). Other researchers, Y. Shao, T. Lefort, S. Moras, D. Rodriguez (Kylili&Fokaides, 2017; Lützkendorf, 2020) report that in order to obtain pozzolanic properties of glass, it is necessary to grind it to a fraction of 0 ÷ 0.125 mm. However, waste glass grain sizes above 0.3 mm can be used as fine aggregate (Czapik et al., 2021; Gawlicki et al., 2013;Szymański,2020; Śliwiński et al., 1997). The Supreme Audit Office reports that sand resources will be exhausted by 2050 (except for quartz sands) (Kuryś&Drabczyk, 2023). The shortage of aggregate is forcing the search for alternative methods of producing fine aggregate (Najduchowska et al., 2014; Czapik et al., 2021).The potential use of recycled glass in the construction sector, in terms of its environmental impact, may have many advantages. Firstly, it influences the reduction of landfill waste, and secondly, it enables the replacement of natural raw materials with recycled ones. These measures aim to reduce the negative impact on the environment, in line with the idea of sustainable development (Rutkowska et al., 2018; Król&Kuterasińska, 2015; Jura, 2017).

The aim of this study was to determine the feasibility of utilising waste ground soda-lime-silicate glass in cement mortar as a reactive pozzolanic additive to cement of 0÷0.1mm fraction or as a non-reactive filler of 0÷2 mm fraction. And to determine the rheological characteristics and parameters of hardened mortar maturing in a laboratory environment as well as in an outdoor environment during winter in the month of February in the area of the Świętokrzyskie Voivodeship in Poland.

Research materials and methods

The test programme comprised three series of mortars in which cement was replaced by 10%, 20%, 30% by weight, and three series in which sand was replaced by 20%, 35% and 50% by weight. Portland cement CEM II/B-V 42.5 R was used for the mortars (Figure 2) in accordance with EN 197-1: 2012. Quartz sand of fraction 0÷2 mm according to PN-EN 12620+A1:2010, tap water (PN-EN 1008:2004) were used as aggregates. All mortar series were made according to the procedure recorded in EN 196-1:2016-07, with w/s = 0.5.

Table 1. Composition of individual construction mortars

Quantity of ingredients, [g]	SW (L,Z)	1C10% L,Z	1C20% L,Z	1C30% L,Z	1S20% L,Z	1S35% L,Z	1S50% L,Z
Cement	450	405	360	315	450	450	450
Sand	1350	1350	1350	1350	1080	472.5	675
Water	225	225	225	225	225	225	225
Glass flour	-	-	-	-	270	877.5	675
Glass dust	-	45	90	135	-	-	-
Superplasticiser	-	-	-	-	3	3	3

Designations: SW – reference series, 1C10% – 10% dust was used as a replacement for cement, 1S20% – 20% glass flour was used as a replacement for sand, etc. Half of the samples from each series were cured under laboratory conditions (designation L), the other half under variable weather conditions outdoors (designation O).

For samples maturing in variable atmospheric conditions (February), the air temperature was measured three times a day at 7:00, 13:00 and 21:00. The graph of air temperature variation is presented below (Figure 1). The samples were placed outside the building on a plastic base approximately 1 cm above the ground, not immersed in water. They were exposed to sunlight, wind and precipitation.

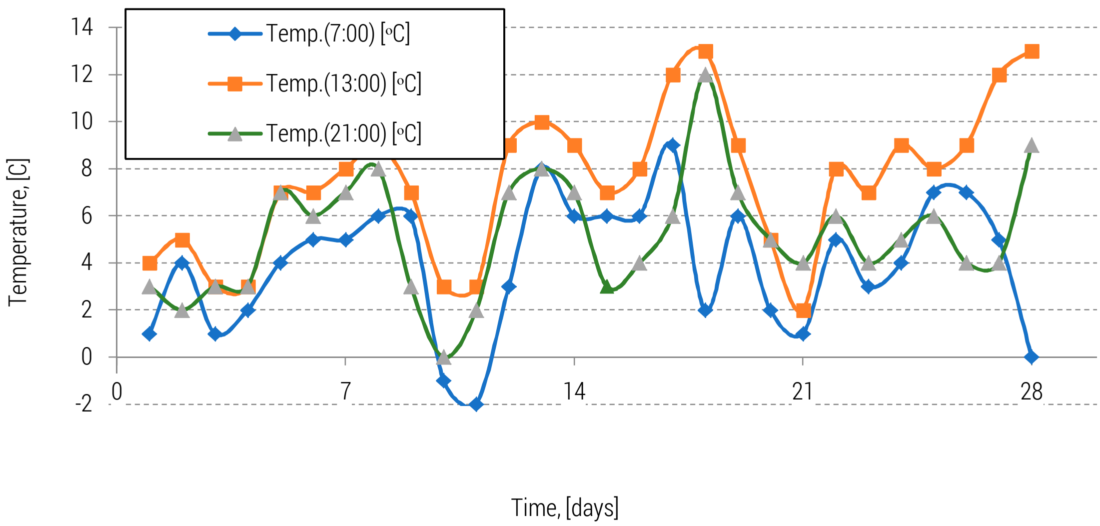

Figure 1. Plot of temperature variation during the maturation of samples influenced by external temperatures

For the first seven days, the temperature varied between +1°C and +5°C. On the eleventh day of maturation, the temperature dropped to -2°C at night. The highest temperature recorded was +13°C.

Portland ash cement CEM II/B-V 42.5 R was used for the mortars. A granulometric analysis of the cement was carried out (Figure 2).

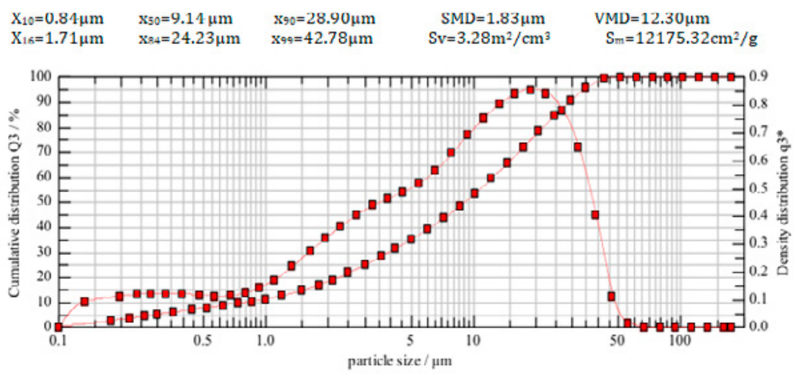

Figure 2. Granulometric analysis of the cement

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Analysis of the granulometric study of the cement (Figure 2) showed that the particle size of 50% of the cement is smaller than 9.14 µm. However, the highest concentration of particles is found in the fraction range from 1 µm to 40 µm.

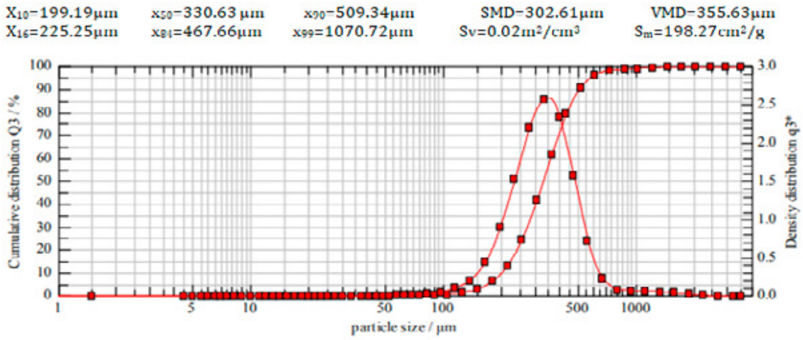

Figure 3. Sand particle size analysis

Based on the data presented in the sand granulometric analysis (Figure 3), it can be concluded that half of the particles (50%) are smaller than 330.63 µm. Furthermore, the highest concentration of particles occurs in the fraction ranging from 150 µm to 350 µm, which indicates a dominant particle size distribution in this range.

Recycled cullet was used in the composition of the mortars, which was substituted for sand at 20%, 35% and 50% by weight. The aggregate was mostly white glass, but coloured glass (green, brown) was also visible. The glass flour used in the mortars was characterised by a grain size of 0-2 mm.

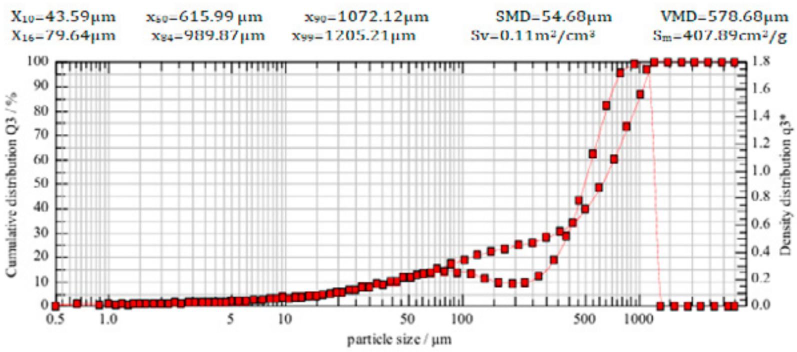

Figure 4. Granulometric analysis of glass flour

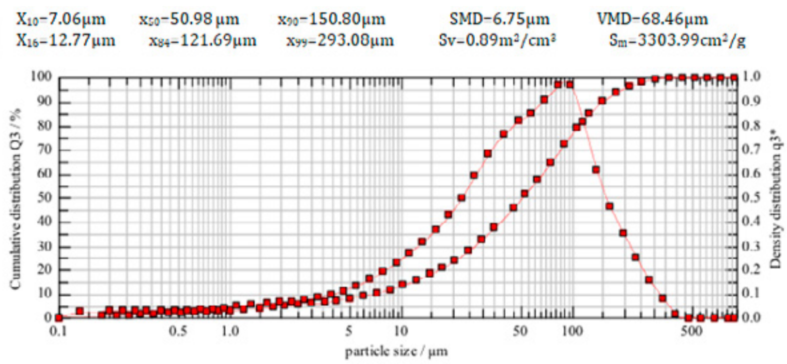

Figure 5. Granulometric analysis of glass dust

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From the data obtained in the glass meal granulometric analysis study (Figure 4), it can be deduced that the glass meal particle size is 50% smaller than 615.99 μm. In contrast, the highest concentration of particles is found in the fraction range from 300 μm to 1050 μm.

Ground glass granules in the form of glass dust replaced cement at 10%, 20% and 30% by weight. It was characterised by a grain size of 0÷0.1 mm.

From the data obtained in the granulometric analysis study (Figure 5) of the glass dust, it can be concluded that the particle size of 50% of the glass dust is smaller than 50.98 μm. However, the highest concentration of particles is found in the fraction range from 7 μm to 400 μm.

Prior to the mortars, EDS analysis of the glass dust was carried out at selected points (Figures 6-8).

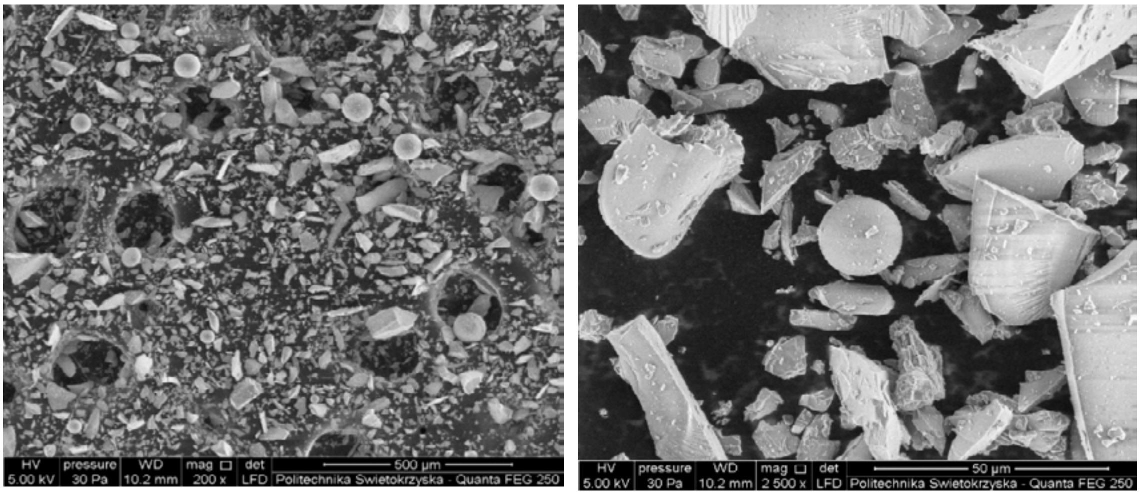

Figure 6. Microstructure of glass dust

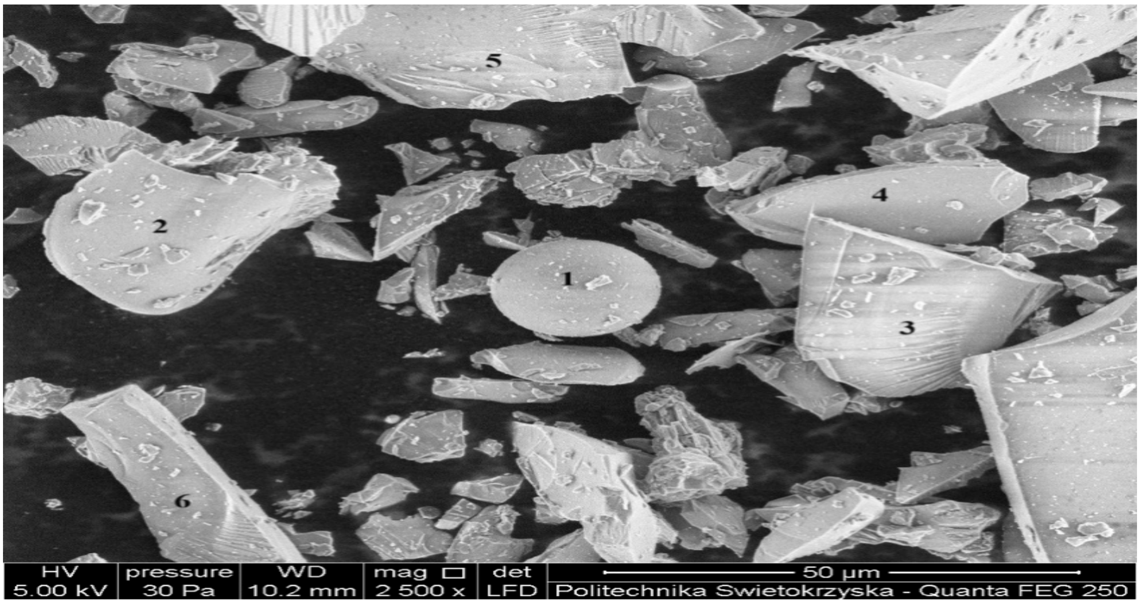

Figure 7. Determination of the points of the tested glass dust microstructure

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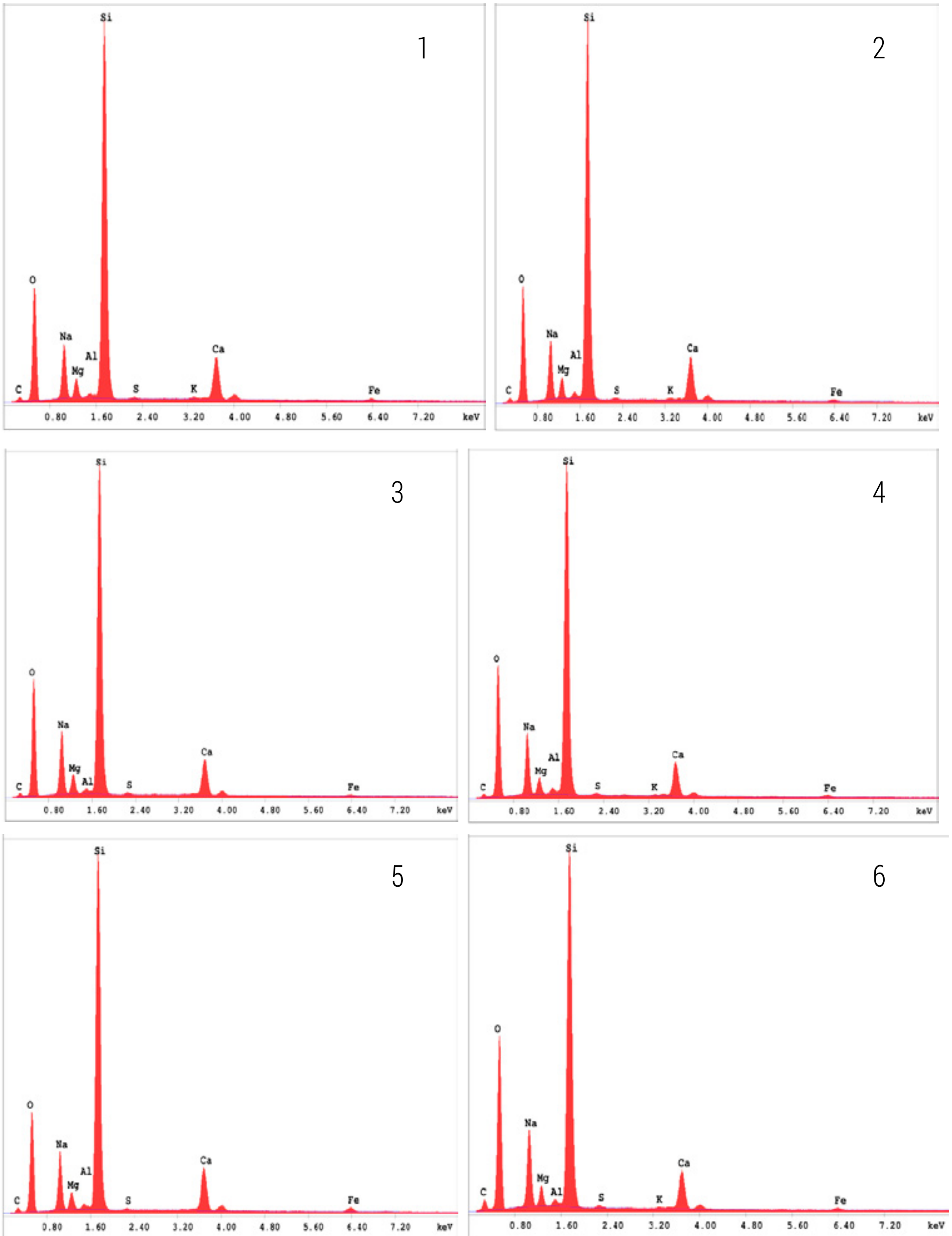

Figure 8. EDS analysis of glass dust

EDS analysis of the glass dust (Figure 8) carried out using a scanning microscope showed that the recycled glass is a soda-lime-silicate glass, due to the predominant amount of sodium oxide and limestone in the test sample.

A superplasticiser was used in the study. It is an advanced product of a new generation of PCE polymers. It is characterised by strong plasticising properties, rapid development of early strength and a moderate reduction in the w/c ratio. The admixture was added directly to the wet mortar components.

The consistency was determined using the flow table method in accordance with PN-EN 1015-3:2000. The consistency test using this method is performed by measuring the flow of fresh mortar on a table plate subjected to shocks at a frequency of 1 shock/s. A conical mould, moistened from the inside with a damp cloth, is placed centrally on the upper plate of the flow table. The mould is filled with two layers of mortar. The level of the mortar is levelled to the upper edge of the mould. After 30 seconds from levelling, the mould is lifted upwards. After lifting the mould, 15 cycles of lifting and free-falling of the upper plate of the table are performed. The determination consisted of measuring the diameter of the mortar spread in two perpendicular directions.

The bulk density test was carried out in accordance with PN-EN 1015-6:2000. For this purpose, a stainless steel vessel with a capacity of 1000 cm^3 was used. The measurement began with weighing the vessel. The prepared mortar was then placed in two layers. After removing the excess mortar and levelling it to the upper edge of the mould, the vessel with its contents was weighed to an accuracy of 1 g. The measurement was performed three times, and the result is the arithmetic mean of the obtained results.

Calculate the volume density of fresh mortar (ϱm) using the following formula:

$$\varrho m = \frac{m2 - m1}{V}. [\frac{g}{cm3}], \tag{1}$$

where:
m1 – empty vessel weight[g],
m2 – vessel weight with mortar[g],
V – vessel volume[cm^3].

Compressive and flexural strength testing was carried out on 40×40×160 mm standard specimens according to EN 1015-11:2020-04. Half of the specimens were matured in the laboratory in water at +18±2°C after forming. The other half of the specimens from each series were subjected to variable maturation temperatures according to Figure 1. Compressive and flexural strengths were tested after 7, 28, 56 days, each time on six specimens from each series.

Capillary rise was tested according to PN-88/B-06250 on 40×40×160 mm specimens. Half of the beads were stored in water at +18±2°C for 7 days after forming, while the other half were matured in air at varying temperatures. The samples from the laboratory conditions were then stored in an air-dry environment at +18±2°C for 21 days. The weight gain of the tested mortars was controlled after 28 days of maturation for all samples. Before testing, the mortars were placed in an air-conditioning chamber at a constant temperature of +40°C for a period of 120 hours. After the samples were removed from the chamber, the weight gain of the mortars was tested 15 min, 30 min, 1 h, 4 h after the samples were in contact with water. Subsequent weight measurements were made every 24 hours. The samples were immersed to a height of approximately 5 mm in water throughout the test period.

The absorbability test was carried out in accordance with PN-88/B-06250 on samples measuring 40×40×160 mm. The mortar samples from the laboratory conditions were stored for a period of 7 days in water at +18±2°C and a further 21 days for the test in air at +18±2°C. And the second part of the samples from each batch was stored outside the building at varying temperatures in the air for a period of 28 days. All samples were then placed in water up to half their height for a period of 24 hours. After one day, the water was replenished to +1 cm above the height of the samples. The weight gain of the tested mortars was monitored every 24 h until there was no weight gain of the tested mortars.

The determination of water absorption and capillary rise was carried out on six samples from each batch, three matured under laboratory conditions and three under varying conditions.

The results of mortar expansion tests were examined in a 1M NaOH solution at a temperature of +80°C, in accordance with ASTM C 1260. The result was given with an accuracy of 0.01% as a measurement for a given period, from three samples from a given series.

The microstructure of the hardened mortar was examined using scanning electron microscopy with a QUANTA FEG 250 device equipped with an EDAX EDS microprobe. Before testing, samples were cut from the hardened mortar into cubes measuring 5×5×5 mm. Dry samples of the material were attached to microscope slides using conductive silver glue. The loose materials under test were fixed to the microscope slides using the pouring method with graphite discs. The analyses were carried out under low vacuum conditions (30 Pa) on samples not coated with a 5 kV electron beam.

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Results of the research

For the consistency determination, the spreading table method was used in accordance with PN-EN 1015-3:2000 (Table 2).

Table 2. Consistency test results for mortars

Series name	Flow [mm]	Consistency class
SW	125x125	Dense plastic
1C10%	125x125	
1C20%	130x130	
1C30%	134x134	
1S20%	100x100	
1S35%	120x120	
1S50%	120x120	

All mortar series tested were characterised by their dense-plastic consistency.The volumetric density test was carried out in accordance with PN-EN 1015-6:2000.

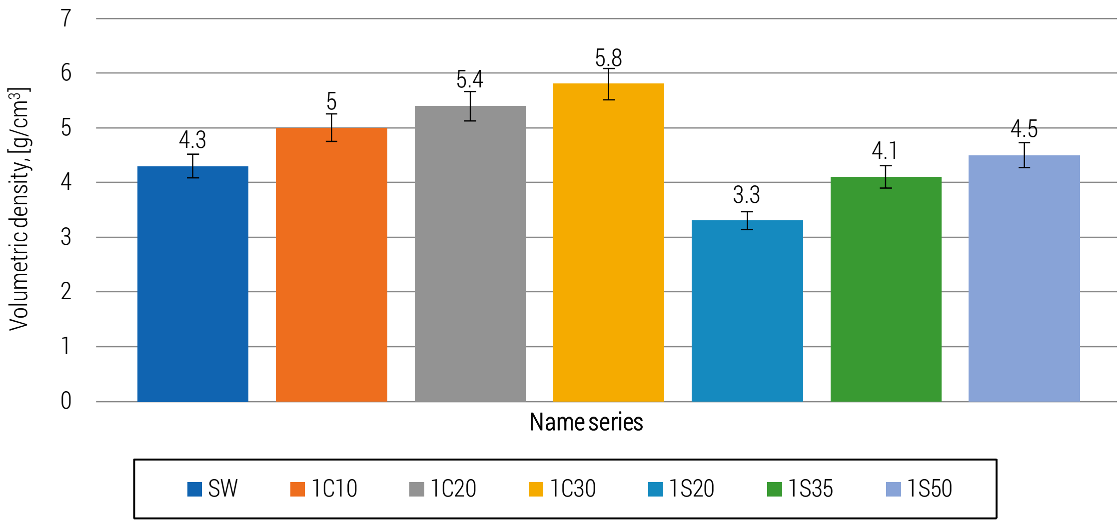

Figure 9. Volumetric density results for the different batches

The use of a cement substitute in the form of glass dust influenced a slight decrease in the volumetric density of the mortars (Figure 9). The more of this substitute, the lower the volumetric density of the mortar. For mortars in which sand was replaced by glass flour with a 0-2 mm fraction, a decrease in this parameter was also recorded. For the 1S50 series, in which sand was replaced by 50% glass flour, the decrease was 9.95% compared with the reference series.

The setting time test was carried out in accordance with EN 96-3:2016-12. A Vicata apparatus was used to determine the setting time.

The use of glass powder as a cement substitute has prolonged the setting time of mortar. The greater the amount of this substitute, the longer the start and end of the setting process, (Table 3).

The flexural strength test was carried out in accordance with PN - EN 1015-11:2020-04 and is shown in Figures 9-10.

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Table 3. Determination of setting time

Name series	Start of setting time, [min]	End of setting time, [min]
SW	210	272
1C10%	232	289
1C20%	263	315
1C30%	290	337

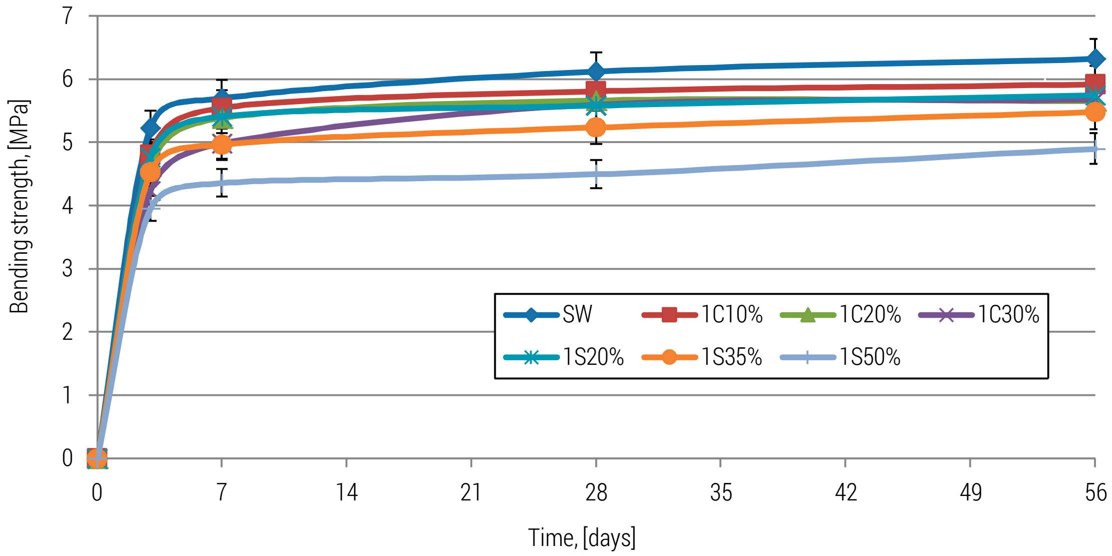

Figure 10. Bending strength graph for the entire series of specimens matured under laboratory conditions

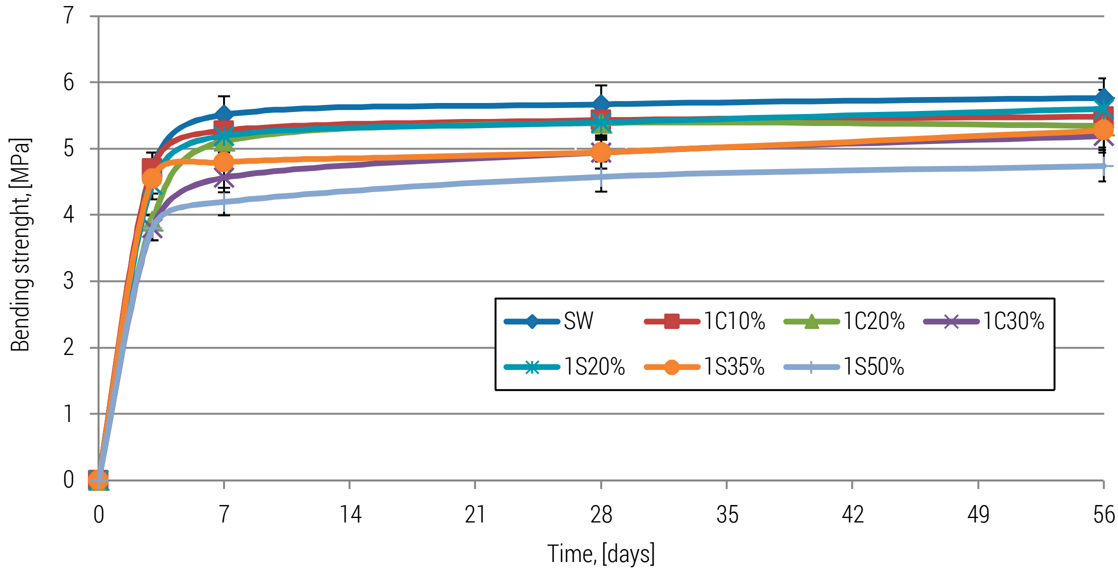

Figure 11. Bending strength chart for the entire series of samples matured under variable atmospheric conditions

Comparing the maturation conditions of the series (Figures 10-11), it can be seen that the samples matured at varying temperatures recorded decreases in flexural strength ranging from 6-8% compared to the series matured under laboratory conditions. The 1C20 and 1C30 series recorded a 9% decrease in strength, while the 1C10 series recorded a 6% decrease after 56 days of maturation. When considering the series in which sand was replaced by flour, the greatest reduction in flexural strength was recorded for series 1S50% at 25%. The prolonged maturation time did not improve this parameter positively.

The compressive strength test was carried out in accordance with EN 1015-11:2020-04.

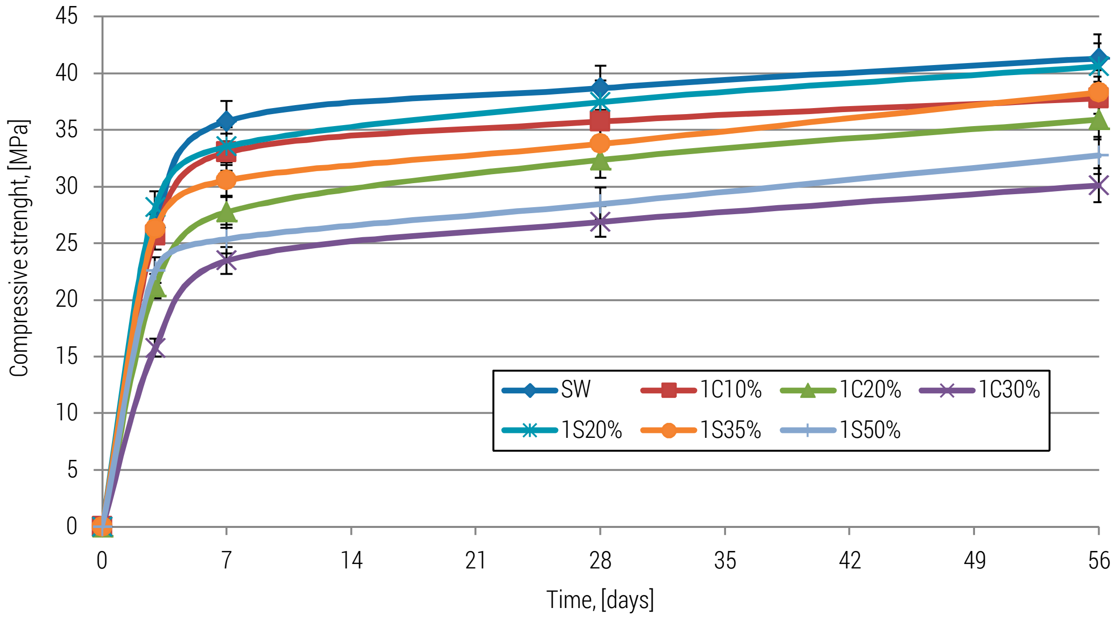

Figure 12. Compressive strength for mortars matured under laboratory conditions

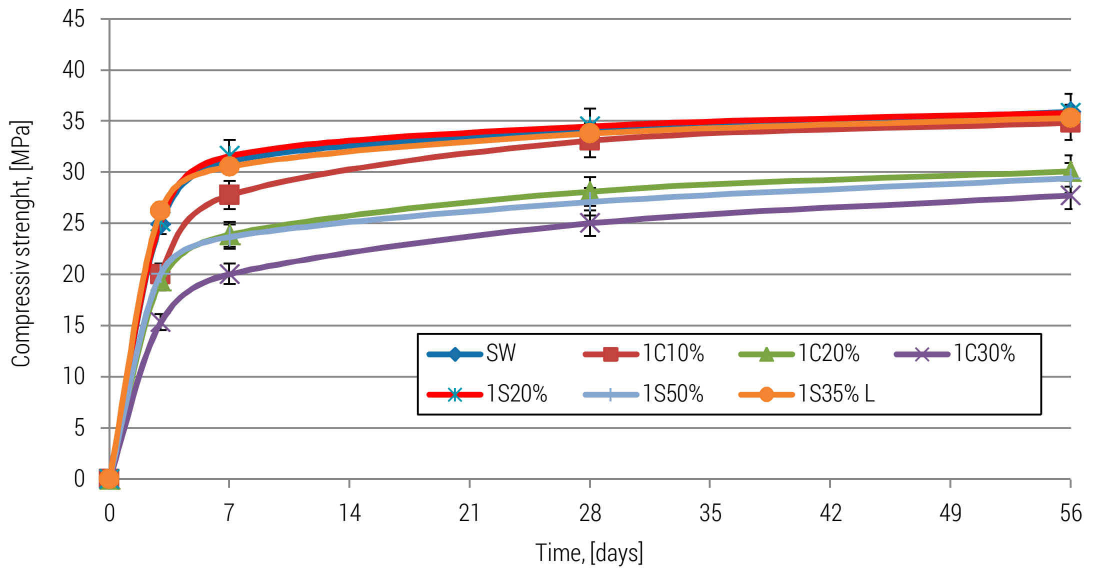

Figure 13. Compressive strength for mortars matured under varying weather conditions

Starting with a comparison of the maturation conditions of the tested series (Figures 12-13), we find that the samples matured at variable temperatures are characterised by a decrease in compressive strength of 13%. The smallest decrease in compressive strength is characterised by the series in which cement was replaced by glass dust at 10% and this decrease is 8.5%. The largest for series 1C30%, i.e. 27%. Comparing the series with sand replacement. The reference series and the 1S20% series received comparable compressive strength gain results. The 1S50% mortar showed the greatest decrease in compressive strength at 20.5%.

Capillary rise was tested in accordance with EN 1015-18:2003, on 40×40×160 mm specimens (Figures 13-14).

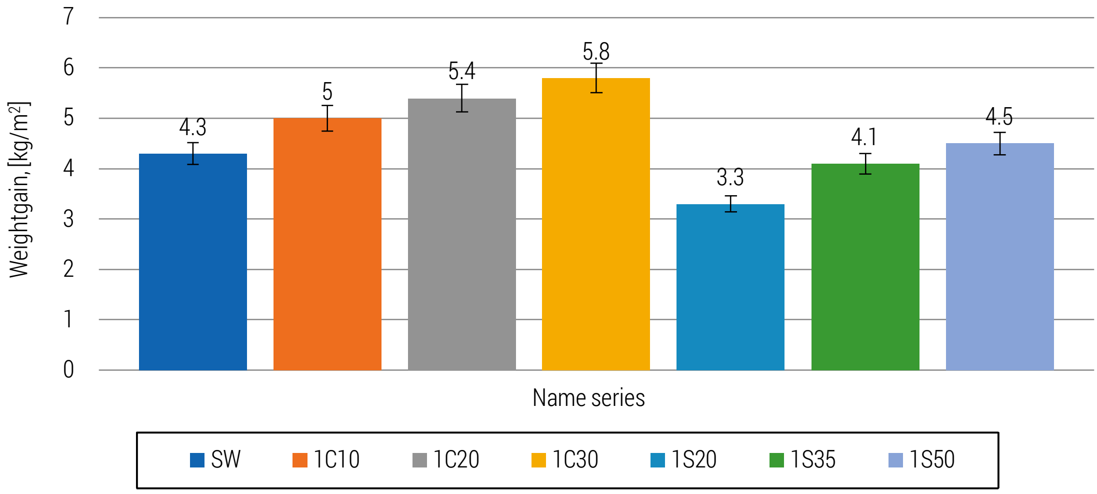

Figure 14. Weight gain in capillary rise determination for samples matured under laboratory conditions

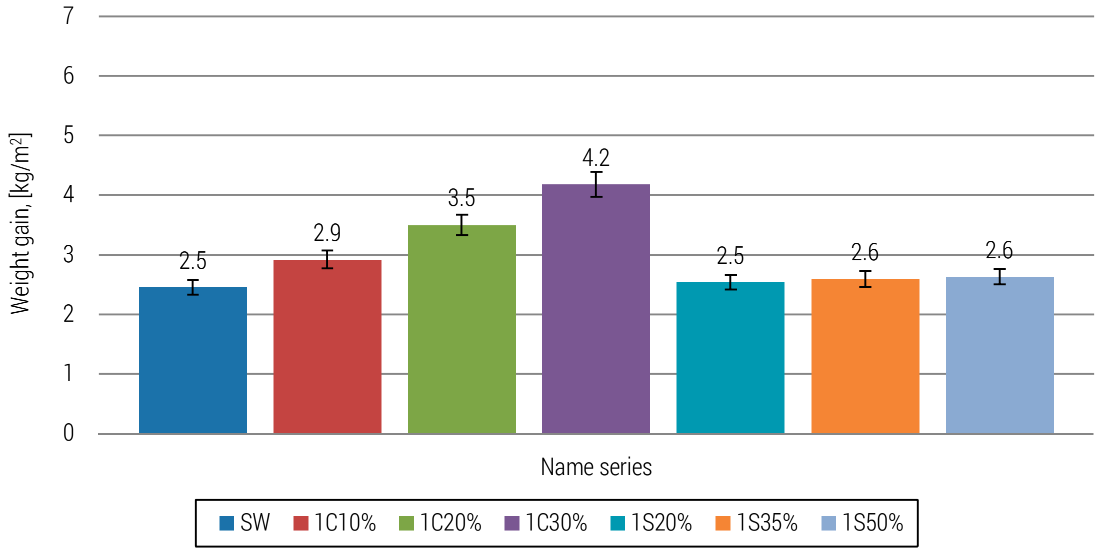

Figure 15. Weight gain in capillary rise determination for mortars matured under variable atmospheric conditions

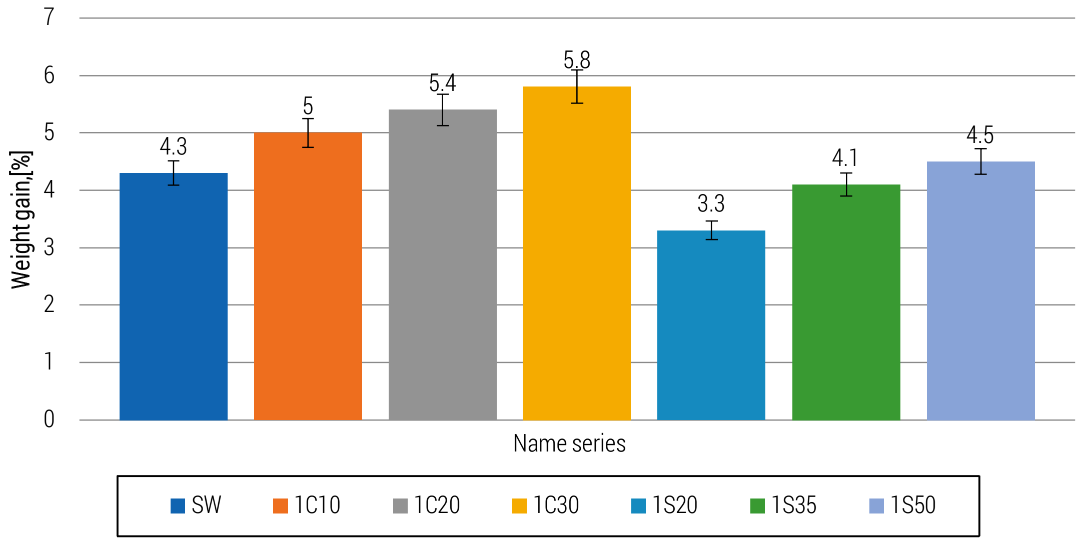

Figure 16. Weight gain in the saturation test of maturing mortars under laboratory conditions

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The series matured under varying temperatures have a higher weight gain of the samples in the test (Figures 14-15). The reference series has a similar weight gain to the 1S20%, 1S35% and 1S50% series. The more cement replacement the greater the weight increase in the mortar capillary rise test. The largest was recorded for the 1C30% series.

The water absorption was tested according to PN-88/B-06250, on specimens measuring 40×40 ×160 mm (Figures 16-17).

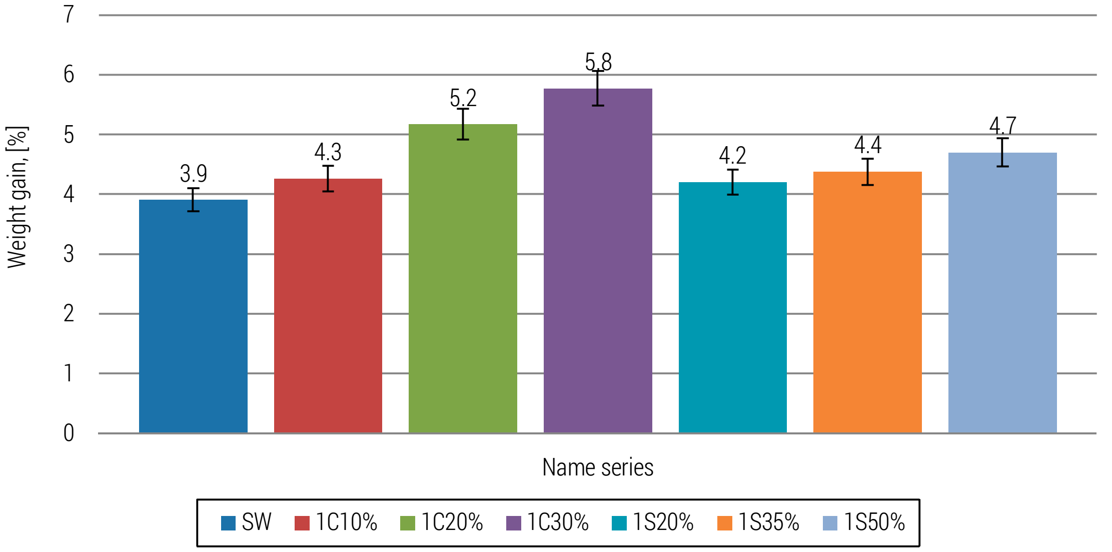

Figure 17. Weight gain in the saturation test of mortar maturing under variable atmospheric conditions

Analysing the weight gain results obtained in the absorbability test, it can be concluded that mortars matured under varying temperatures were characterised by a higher weight gain. Mortars in which cement was replaced by glass dust showed a higher weight gain compared to the reference series. A similar trend was also observed for the mortar series in which sand was replaced by glass flour. The more flour instead of sand, the greater the weight gain in the series tested.

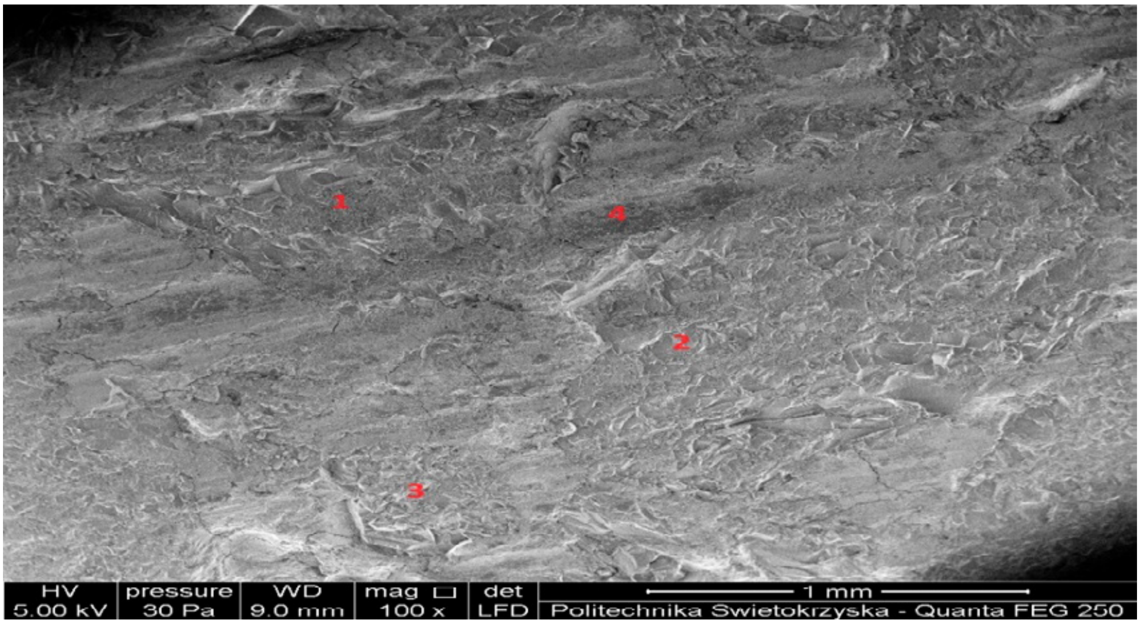

Figure 18. Microstructure area of the 1C350%/L mortar with analysed points

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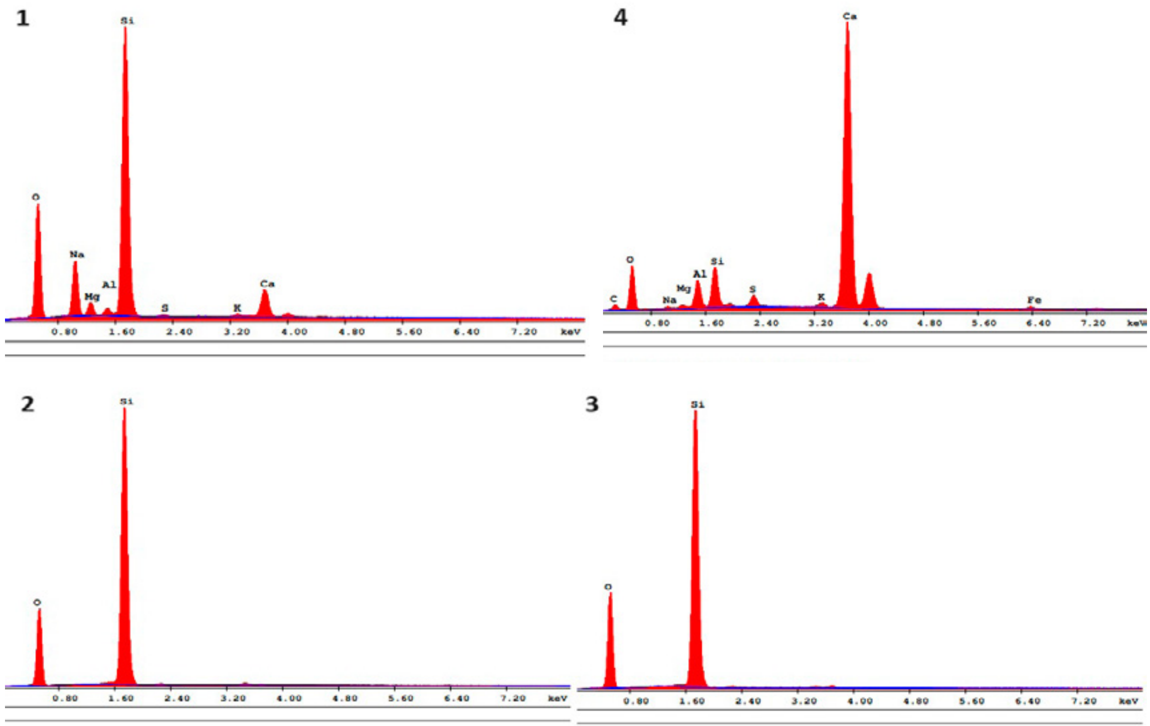

Figure 19. Chemical composition analysis of the point 4 area of the 1S35%/L sample

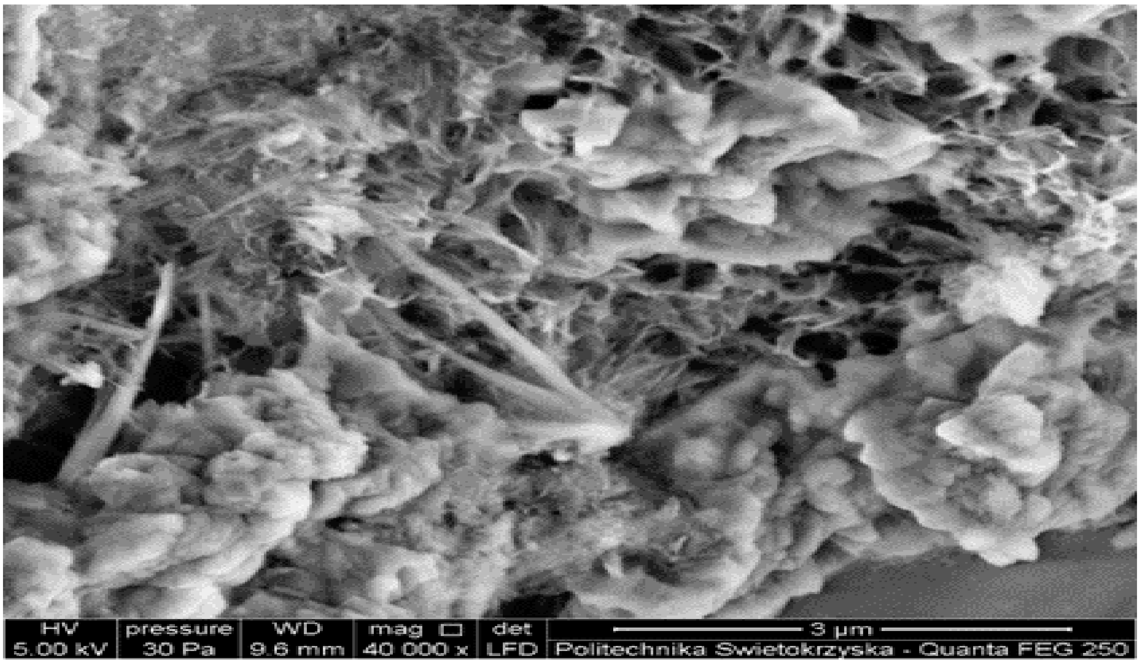

Figure 20. Sample hydration products 1P35%/L at point 4

In the area of point 1 of the analysed sample, glass crystals were observed - glass flour, which is composed of silicon oxide and in small amounts of sodium and calcium oxide. The glass crystals have very irregular shapes compared to the fine aggregate, sand. The analysis at 2 and 4 shows a very high presence of silicon oxide, indicating the aggregate content of the sample structure. The chemical composition at point 4 consists mainly of calcium oxide and, in smaller amounts, silicon oxide, aluminium, sulphur, potassium, carbon, iron, which are all components of the hydration process (Figures 18-20).

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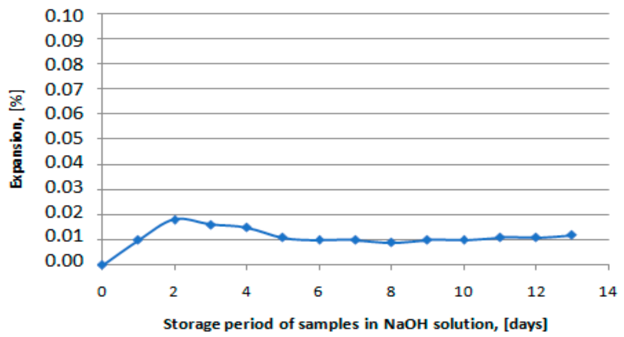

Figure 21. Results of tests on the reactivity of waste glass in the context of alkali-silica reactions

Results of tests on the reactivity of waste glass in the context of alkali-silica reactions (Figure 21). The results of mortar expansion tests in a 1M NaOH solution at 80°C, in accordance with ASTM C 1260, showed that expansion did not exceed the threshold of 0.1%. This suggests that under standard conditions, the glass does not exhibit reactivity, which is consistent with the results of studies conducted (Najduchowska M., Pabiś E., Rolka G. and Barana T. (2016). However, the results of studies by other authors, such as Jin et al. (2000)and Park and Lee (2004) indicate a greater susceptibility of brown glass to the alkali-silica reaction. Park and Lee found that after only 6 days of testing, the expansion could exceed 0.2%, which is the threshold value for a potentially dangerous reaction. In addition, earlier studies (Czapik et al., 2021) have shown that glass can cause significant mortar cracking when in prolonged contact with NaOH solution. Glass does not exhibit reactivity, which confirms its suitability for practical use. However, this reaction must be taken into account in long-term assessments.

Discussion/Limitation and future research

The aim of this study was to determine the feasibility of utilising waste ground soda-lime-silicate glass in cement mortar as a reactive pozzolanic additive to cement of 0÷0.1 mm fraction or as a non-reactive filler of 0÷2 mm fraction. Analysis of the chemical composition of the C-S-H phase point for the 1C10% series showed a high concentration of silicon. Which means that there may be glass dust in the grout matrix. The C-S-H phase resembles a honeycomb in appearance. According to the researchers, this appearance is characteristic of grout without mineral additives (PN-EN 196-1:2016-07). On the basis of the examination of the microstructure of the mortars, it was not found that the pozzolanic reaction was fully taking place. This could also be confirmed by the decrease in compressive and flexural strengths of the tested series.

Based on research conducted by Najduchowska M., Pabiś E., Rolka G. and Barana T. (2016), it can be concluded that the addition of glass cullet to mortar after 28 days of curing affects its compressive strength. The greatest decrease in strength, reaching approximately 35%, was observed when 10% and 20% of glass cullet was used in comparison to the reference series. In the case of a 50% addition of glass cullet, the decrease in strength was similar. The remaining results indicate that with a 10% addition of glass powder, the decrease in strength was a maximum of 20%, and with 30% – approximately 35%. These conclusions are consistent with each other and confirm that the above amounts of glass powder can lead to a significant reduction in compressive strength. These results are very similar.Czapik et al. (2021) statedthat the use of glass waste as both a binder substitute and aggregate affects the strength parameters of mortar (compressive and flexural strength). When cement is replaced with glass dust, this is associated with a reduction in the binder content and is proportional to this content.

Analysing the results of the weight gain obtained in the absorbability test, it can be concluded that mortars matured at varying temperatures had a higher weight gain. Mortars in which the cement was replaced by glass dust showed a higher weight gain compared to the reference series. A similar trend was also observed for the mortar series in which sand was replaced by glass flour. The more

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flour instead of sand, the greater the weight gain in the tested series.Rutkowska et al. (2018) found in their study that changing the amount of ground glass as a cement substitute did not result in a significant weight gain in the soakability test.

The use of a cement substitute in the form of glass dust resulted in a slight decrease in the volumetric density of the mortars. The more of this substitute, the lower the volumetric density of the mortar. Similar laboratory results were obtained by Czapik et al. (2021).

According to literature data, glass ground to a fraction of up to 0.3 mm shows pozzolanic properties. It is then a potential replacement for cement. This is also confirmed by studies carried out byGołek et al. (2020), as well as researchers Y. Shao, T. Lefort, S. Moras, D. Rodriguez (Kylii &Fokaides, 2017; Lützkendorf,2020) state that in order to obtain pozzolanic properties of glass, it is necessary to grind it to a fraction of 0÷0.125 mm. In this study, glass with a fraction of 0÷0.1mm was used, which did not show full pozzolanic properties. The use of such dust as a partial substitute for cement affects the physical and mechanical properties of mortars, causing a deterioration in mortar parameters, i.e. compressive strength and flexural strength.

Further tests are planned on a different type of glass, as even glass of a different colour may exhibit different properties. Factors influencing the reactivity of the additive include, among others, the grain size of the ground glass. In subsequent laboratory tests, we will use finer dust than that used in the tests described here due to the observed decreases in the strength parameters tested. No complete pozzolanic reaction was observed, which, according to numerous researchers, should occur. The studies did not observe any adverse effect of the reaction of sodium hydroxide and potassium hydroxide with active silica on strength and microstructure. However, based on previous experience and knowledge from the literature, further studies are necessary to verify whether such a reaction will occur at a later stage.

Conclusions

As a result of the analysis of the tests carried out, the following conclusions were drawn:

1. All tested mortar series were characterised by a thick-plastic consistency. Dry sand with a density of 2.62 g/cm^3 was used for the tests. At the same time, it was found that an increase in the proportion of glass dust replacing cement (density 3.16 g/cm^3) caused a deterioration in the workability of the mortar. This may be due to an increase in the proportion of dust fractions. This is caused by the difference between the density of cement and the density of glass. Similar results were obtained in laboratory tests carried out by Czapik et al. (2021).
2. Cement substitute in the form of glass dust with a grain size of 0 ÷ 0.1 mm and glass flour with a grain size of 0÷2 mm as a substitute for sand affected the volume density. The more substitutes, the lower this density. This may indicate a lower water content of dust and glass flour compared to cement and sand.
3. Series 1C20 and 1C30, in which cement was replaced at 20% and 30%, recorded a strength drop of 9%, while series 1C10 (10% dust) recorded a 6% drop after 56 days of maturation. When glass dust was used as a cement replacement, the decrease in compressive strength was around 10%. When considering the series in which sand was replaced by flour, the greatest decrease in flexural strength was recorded for the 1P50% series at around 25%. Increasing the maturing time did not significantly improve the parameter considered. Therefore, it can be concluded that this is not due to the chemical processes in the mortars. The reduced compressive and flexural strength parameters of the mortars modified with dust and glass flour may be due to the low density of glass and its irregular shape compared to the more regular shape of the sand grains. Air voids are more likely to form between the dust and glass flour, negatively affecting the strength performance of mortars.
4. The smallest decrease in compressive strength was observed for the series in which cement was replaced with glass dust at a rate of 10%, and this decrease was 8.5%. The largest decrease was recorded for series 1C30%, i.e. 27%, which corresponds to the degree to which the cement was replaced by glass dust. Thus, it cannot be concluded that the glass dust tested exhibits full pozzolanic properties. Partial pozzolanic properties may be evidenced by the hydration envelopes vis-

ible under the scanning microscope around the glass grains. Evidence could also be found in the sodium present in the hydration products from the dissolved glass.
5. Mortars curing under variable atmospheric conditions (outdoors, in winter) exposed to sunlight, wind, frost, and precipitation, show a 13% decrease in compressive strength compared to mortars curing under laboratory conditions. A similar trend was observed for flexural strength testing. In this case, the decrease ranges from 6 to 8% compared to the series maturing under laboratory conditions.
6. In the course of tests carried out in accordance with ASTM C1260, (ASTM, 2023), no adverse effect of the reaction of sodium and potassium hydroxide with activated silica on strength and microstructure was observed. The expansion achieved did not exceed the 0.1% threshold when tested for 14 days according to the standard. This is probably related to the large specific surface area of the cullet used. However, in light of literature reports (Kurdowski, 2010; ASTM, 2023), further studies are necessary to verify that such a reaction does not occur at a later stage.

The contribution of the authors

Conceptualisation, A.K. and I.J.; literature review, I.J.; methodology, A.K.; formal analysis, A.K. and I.J.; writing, A.K. and I.J.; conclusions and discussion, A.K. and I.J.

The authors have read and agreed to the published version of the manuscript.

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WYKORZYSTANIE PRODUKTÓW ODPADOWYCH W POSTACI PYŁU I MĄCZKI SZKLANEJ W ZAPRAWACH

STRESZCZENIE: Rozwój ekoinnowacji w przemyśle materiałów budowlanych odgrywa kluczową rolę w promowaniu zrównoważonego rozwoju. W obliczu kurczących się zasobów naturalnych producenci materiałów budowlanych coraz częściej sięgają po rozwiązania, które zmniejszają negatywny wpływ na środowisko, zapewniając jednocześnie wysoką jakość produktów. Celem badań była ocena możliwości wykorzystania odpadowego szkła sodowo-wapniowo-krzemianowego jako reaktywnego dodatku pucolanowego do zapraw cementowych lub jako wypełniacza niereaktywnego. Badania obejmowały przygotowanie serii zapraw o różnym stopniu zastąpienia cementu pyłem szklanym (10%, 20%, 30%) oraz serii, w których piasek zastąpiono mączką szklaną (20%, 35%, 50%). Badano czas wiązania, gęstość nasypową, konsystencję, wytrzymałość na ściskanie i zginanie, wodochłonność i kapilarność, a także mikrostrukturę zapraw. W przypadku zastosowania pyłu szklanego jako substytutu cementu spadek wytrzymałości na ściskanie wynosił od 8,5 do 16%, a spadek wytrzymałości na zginanie od 6 do 9%. Mielony pył nie wykazywał pełnych właściwości pucolanowych.

SŁOWA KLUCZOWE: dodatek, szkło, wytrzymałość na ściskanie, nasiąkliwość, podciąganie kapilarne

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