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INFLUENCE OF THE WASTE GLASS USES ON THE CEMENT MORTAR PROPERTIES

WPŁYW STOSOWANIA SZKŁA ODPADOWEGO NA WŁAŚCIWOŚCI ZAPRAWY CEMENTOWEJ

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A b s t r a c t

In this paper the influence of waste glass on the properties of cement mortar was described. The coloured waste glass in two different forms was used: the glass cullet with a particle size of 0.125-4.00 mm as a fine aggregate and the glass powder with a particle size below 0.125 mm as cement replacement. Both types of glass were obtained by crushing and milling brown glass bottles. The tests were carried out on mortars in which sand was entirely replaced by glass cullet or 20% of cement was replaced by glass powder. The effect of glass cullet and glass powder on the properties of cement mortar, such as setting time, consistency, flexural and compressive strength was determined. Moreover, the role of glass cullet as a potential source of expansion resulted from the alkali-silica reaction was investigated. The microstructure of hydrated composites was also examined with a scanning electron microscope.

Keywords: waste glass, glass cullet, glass powder, cement mortar, physical interaction

S t r e s z c z e n i e

W niniejszym artykule opisano wpływ szkła odpadowego na właściwości zaprawy cementowej. Do badań zastosowano barwione szkło odpadowe w dwóch formach: stłuczki szklanej o uziarnieniu 0,125-4 mm wykorzystywanej jako kruszywo drobne i mączki szklanej o uziarnieniu poniżej 0,125 mm wykorzystywanej jako zamiennik cementu. Oba rodzaje szkła uzyskano w wyniku kruszenia i mielenia brązowych szklanych butelek jednego pochodzenia. Badania prowadzono na zaprawach, w których piasek w całości został zastąpiony stłuczką szklaną lub cement w 20% został zastąpiony przez mączkę szklaną. W pracy określono wpływ stosowania stłuczki szklanej i mączki szklanej na podstawowe własności technologiczne zaprawy cementowej, tj. na czas wiązania, konsystencję oraz wytrzymałość na ściskanie i zginanie. Ponadto określono czy stosowanie stłuczki szklanej może być przyczyną wystąpienia ekspansji na skutek zachodzenia reakcji alkalia-krzemionka. Zbadano też mikrostrukturę próbek pod skaningowym mikroskopem elektronowym.

Słowa kluczowe: szkło odpadowe, stłuczka szklana, mączka szklana, zaprawa cementowa, oddziaływanie fizyczne

1. INTRODUCTION

Concrete is one of the most widely used construction materials in the world. Many scientific papers have been written on the research of the technology of its production. A number of them focus on the possibility of utilising various waste materials from other industrial sectors for the production of both concrete, as well as the binder itself. The use of such materials could affect the properties of concrete in different ways. Granulated blast-furnace slag, which for many years was considered to be a waste product and was stockpiled in heaps, is now a desirable material for the production of cement [1]. Binders containing granulated blast-furnace slag, as well as other mineral

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additives which, according to standard PN-EN 206 [2] are classified in the II group, may improve the properties of concrete and affect its strength and durability. Other waste materials do not have such favourable properties but may act as type I additives in concrete and can be utilised as fillers. However, when using such materials it is necessary to avoid adding any components to concrete that could be detrimental and reduce its durability. It would be especially harmful if concrete contained any internal corrosion-promoting components [1, 3]. This type of degradation can be even more dangerous than degradation generated by environmental factors because it can be present across the whole volume of the concrete, rather than gradually advancing from its surface. Factors which can potentially be found in waste materials, and which could reduce the durability of cement composites are sulphates, chlorides and reactive silica. Waste glass is one of the waste materials that could potentially be entirely made of reactive silica.

Glass is one of the materials that is suitable for recycling and can be relatively easily re-used when melted down. In Europe, glass recycling techniques are among the most advanced, and in some countries up to 85% of glass containers are produced from recycled glass [4]. In Poland, however, only a relatively small percentage of glass is melted down. A large share of glass containers and glass cullet obtained from them are deposited at municipal or illegal dump sites. Therefore, there is a problem of their possible re-use.

In the context of concrete technology, waste glass can be potentially utilised in two ways – as a non-reactive filler, or as a reactive pozzolanic additive. The form in which waste glass is used in the production of concrete depends mainly on its particle size and its reactivity. It is usually assumed that pozzolanic properties may be demonstrated by glass of a particle size below 0.038-0.3 mm [5, 6], and that in this form it can be used as a cement substitute. Waste glass with a greater particle size can be used as aggregate. In this form, as opposed to glass used as a pozzolanic additive, its high chemical activity is not desirable, as it may cause the degradation of concrete as a result of an alkali-silica reaction. This activity depends on the chemical composition and particle size of glass. Numerous papers [5, 7-12] have been written on the process of the glass pozzolanic and the alkali-silica reaction. The research examined issues such as how the use of different types of glass affects these processes. Previous tests [12] analysed the process of degradation resulting from the alkali-silica reaction in mortars that were made using waste glass obtained through the crushing of selected containers of the same type. It was observed in these tests that during the standard period of testing, glass cullet does not necessarily have to cause a harmful alkali-silica reaction.

The aim of this paper is to analyse the effect of this "harmless", i.e. non-reactive glass, on the main technological properties of mortar, when used both as a finely-ground glass powder, or as fine aggregate instead of the quartz sand fraction, with a 1:1 mass ratio. The use in the tests glass, which will potentially not react with the cement paste components (in pozzolan or alkali-silica reaction), is to prove its physical influence on the mortar properties. This is supplement to numerous research on the glass chemical influence on the mortars.

2. MATERIALS FOR TESTING

During the tests, CEM I 42.5R cement was used as the binder. Sand as per standard CEN PN-EN 196-1 [13] and glass cullet from waste glass were used as the aggregate. Waste glass was also used in the form of glass powder. Glass cullet and powder were obtained as a result of the crushing and milling of brown glass containers of the same origin. Glass was milled using a ball mill with steel balls. After being crushed, waste glass was divided into separate fractions in the course of a screening process. Glass fractions of 0-0.125 mm were classified as powder. The particles of bigger fractions were used to create piles of aggregates with particle sizes required for quartz sand for mortars for the purposes of the specific tests.

Table 1 shows the used cement and glass chemical composition. It demonstrates that the tested glass is soda-lime glass. The density of cement and glass was 3.250 kg/m^3 and 2.495 kg/m^3 respectively.

The tests were carried out on cement paste and mortar samples prepared with a w/c ratio of 0.5. The tests were carried out on samples in which the 100% mass of sand aggregate was replaced with glass

Table 1. Chemical composition of cement and glass [%]

Material	SiO	CaO	Al_2O_3	MgO	Fe_2O_3	Na_2O	K_2O	SO_3	Cl
Cement	19.07	63.99	5.43	1.66	2.79	0.25	0.99	3.41	0.069
Glass	63.89	11.65	4.00	1.25	–	19.21	–	–	–

cullet, or in which 20% mass of the cement binder was replaced with glass powder. Only quartz sand was used as aggregate in mortars with glass powder.

3. TESTING METHODS

In the case of testing binder with a glass powder additive, the effect of the use of this additive on the onset of setting was determined on cement paste samples in accordance with procedures defined in standard PN-EN 196-3 [14], as was its effect on phase changes. Cement paste served as a reference sample. Phase changes present in the period of 28 days were tested via x-ray diffraction, using an Empyrean (PANalytical) diffractometer. The pastes for these tests were kept in plastic bags, wherein after 24 hours distilled water was added to these bags to ensure adequate curing conditions.

The consistency of mortar containing standard aggregate or glass cullet was determined using the flow table test in accordance with the PN-EN 1015-3 standard [15], as well as compressive and flexural strength in accordance with the PN-EN 196-1 standard [13] after 2, 7 and 28 days. The particle size of glass cullet used for the production of this mortar was the same as the particle size of standard sand according to CEN PN-EN 196-1 [13]. Standard cement mortar containing quartz sand was used as reference mortar.

The microstructure of fractured 28-day mortar samples was also tested using a Quanta FEG 250 (FEI) electron scanning microscope equipped with an EDS (EDAX) X-ray microanalyser. Analyses were carried out in low-vacuum conditions (30 Pa), on unsprayed samples, using a 5 kV electron beam.

Additionally, the results of alkaline reactivity tests on glass cullet, carried out using the accelerated method as per ASTM C 1260 [16], were demonstrated.

4. PRESENTATION OF TEST RESULTS

4.1. Results of tests of cement paste with glass powder

Table 2 shows the results of the testing of the initial setting time of a binder in which 20% of cement was replaced with glass powder, in comparison to the results achieved for pure cement binder. It was observed that the tested powder, as well as the use of fly ash [17], extend the period of time which precedes the initial setting time of the binder.

Table 2. Setting time

Binder	Initial Setting Time [min]
CEM I 42.5R cement	415
Cement binder with glass powder	450

Following the bonding of cement with glass powder, tests of the phase changes taking place in this cement during the period of 28 days were tested, as illustrated in Figure 1. It demonstrates diffraction patterns made after 3 and 24 hours and after 28 days of the curing of the cement paste. They primarily reveal peaks generated by clinker phases and by products obtained as a result of their hydration, mainly portlandite. The analyses of the reference paste and the paste containing glass powder, which were carried out at different dates, demonstrate differences in the intensity of various phase peaks. The background also rises with time, indicating the formation of an amorphous C-S-H phase. In the case of glass-containing paste, lower reflections from portlandite can be observed. However, this is not necessarily the result of its participation in the pozzolanic reaction [1, 17, 18]. It is related to the lower content of cement in this sample. This is evidenced by the lower intensity alite peaks, the hydration of which is the main source of portlandite present in the cement paste [1]. The increase of the portlandite peaks in the cement paste and in the glass powder-containing paste, combined with the reduction of clinker phases and gypsum peaks, can be observed mainly during the first 24 hours. No reduction of portlandite reflections indicating the pozzolanic properties of glass powder, was observed after this period.

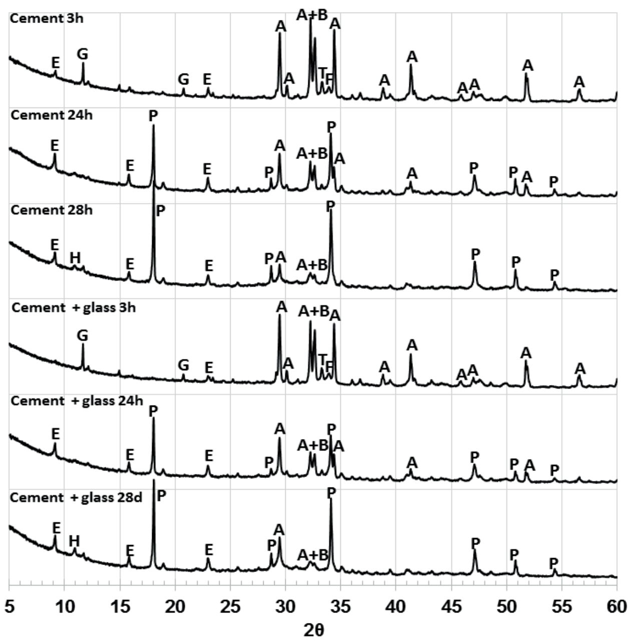

Fig. 1. Diffraction pattern of pastes made using cement binder and a mixture of 80% cement and 20% glass powder recorded after 3 and 24 hours and 28 days of hydration: A – alite, A+B – area of reflections common for alite and belite, E – ettringite, F – brownmillerite, G – gypsum, H – C-S-H, P – portlandite, T – C3A

Table 3. Properties of mortars with waste glass

Mortar	Consistency [mm]	Flexural strength after No. of days [MPa]			Compressive strength after No. of days [MPa]		
		2	7	28	2	7	28
CEM I 42.5R cement	144	6.1	7.3	8.3	30.9	43.9	51.2
Cement mortar with glass powder	158	4.9	6.0	7.0	24.9	34.3	40.6
Cement mortar with glass cullet	108	4.5	4.9	5.1	22.3	32.3	34.7

4.2. Results of the testing of mortars with waste glass

Table 3 shows a list of results of the comparison of the effect of waste glass in the form of powder and cullet on cement mortar technological properties.

Figure 2 illustrates the comparison of mortar consistency measured using the flow table test. It demonstrates that waste glass in the form of powder, used instead of cement and in the form of cullet instead of sand, has a different effect on mortar flowability. The use of glass cullet caused a significant reduction in flowability and only a limited flow was achieved. This may indicate a higher water demand of glass cullet than in the case of standard sand. It was also observed that the replacement of cement with glass powder caused higher flowability. The introduced glass, unlike cement, does not react with water in hydration processes, so it does not reduce the liquid phase content in the system. This and the larger glass powder grains size contribute to its lower water demand compared to cement. The increase flowability could be also a result of the increase in the volumetric content of fine fractions in the mortar. This is due to the different density of cement and glass which replaces it. A reverse effect was achieved when replacing sand with glass cullet. In this case, the replacement of sand with lighter glass results in a higher volumetric content of aggregate in the mortar, and therefore the reduction of the content of dusty/ultra-fine fractions, which is unfavourable in the context of workability [18]. Changes in the volume of binder and aggregate resulting from the use of waste glass are very low and amount to less than 1%.

Figures 3 and 4 illustrate the effect of waste glass on the values of the flexural strength and compressive strength of mortar in a period of 28 days. The use of glass powder, as well as glass cullet, resulted in lower strength values in comparison to the reference sample. In the case of the use of glass powder instead of cement, strength values were always lower by approximately 20%, which corresponds to the percentage of cement that was replaced by finely-milled waste glass. Thus, the pozzolanic properties of the tested glass powder could not be confirmed.

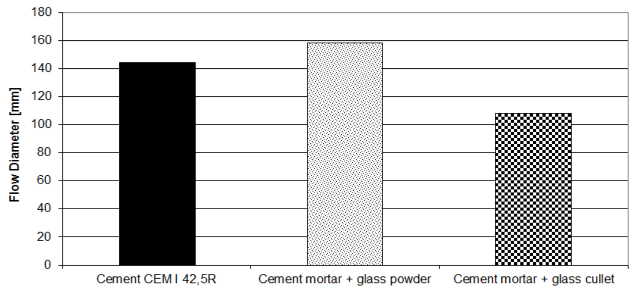

Fig. 2. Consistency of mortars

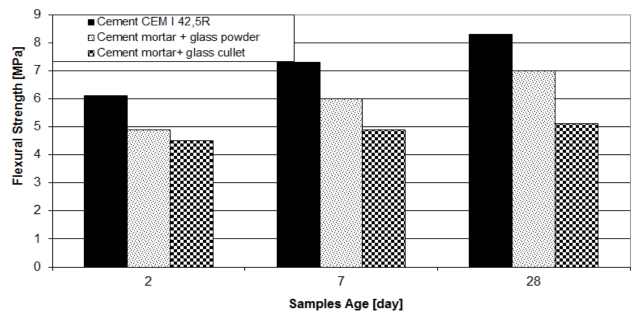

Fig. 3. Flexural strength

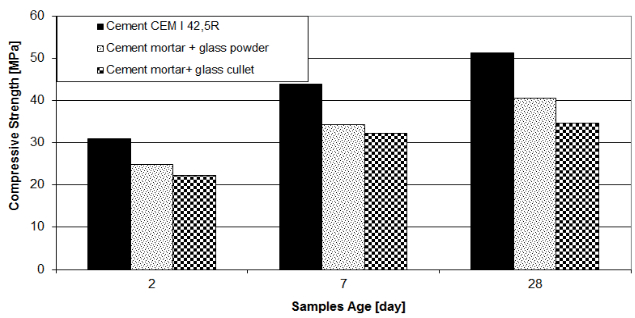

Fig. 4. Compressive strength

Higher reduction of strength values was observed when using glass cullet as aggregate, amounting to approximately 30%. However, the percentage reduction of strength in comparison to the reference mortar is constant over time, as is the case with glass powder-containing samples. It can therefore be concluded that it is not caused by chemical processes. It may be caused by the properties of glass itself, as well as by the properties of the resulting paste-aggregate interfacial transition zone. In order to verify this, testing of the microstructure of the prepared mortars was subsequently carried out.

Figures 5, 6 and 7 illustrate the microstructure of mortar with glass powder and cullet. In the case of the microstructure of mortar with glass powder (Fig. 5), fine glass particles are visible as embedded in the C-S-H phase. The resultant C-S-H phase has obtained a fibrous or “honeycomb” form (Fig. 6), which is characteristic of the setting process of cement without mineral additives [1]. No amorphous, compact microstructure, which was visible during the hydration of cement in the presence of glass powder with pozzolanic properties, was observed [1, 11]. An analysis of the elemental composition of the C-S-H phase revealed significant indications of silicon, which can be attributed to the presence of glass particles dispersed in the cement paste matrix.

Figure 7a illustrates the microstructure of mortar with glass cullet. Many of the glass particles have an elongated, flat shape. This differentiates glass cullet from sand, which normally has more regular particles. The glass powder particles visible in Figure 5 also have the form of a thin plate. This would suggest that glass particles have a larger specific surface area than sand particles. This, together with the difference between the density of glass and sand, is another reason which would explain the lower liquidity of mortar with glass cullet, because a larger specific surface area causes higher water demand [18, 20]. Air voids can also form more easily between irregular aggregate particles, and more cement paste is needed to fill them, which can result in lower strength parameters of the mortar.

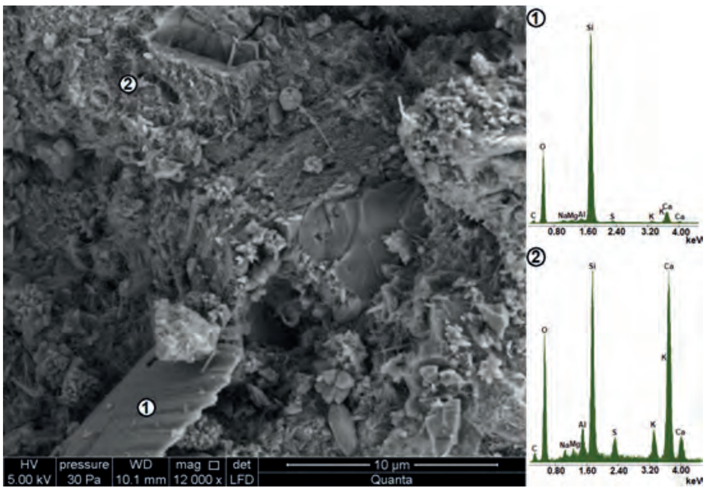

Fig. 5. Microstructure of the fracture of mortar with glass powder and EDS analyses in points 1 and 2

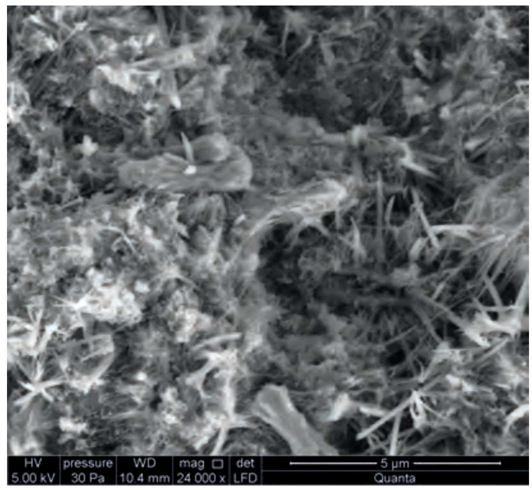

Fig. 6. C-S-H phase with ettringite in the matrix of cement paste with glass powder

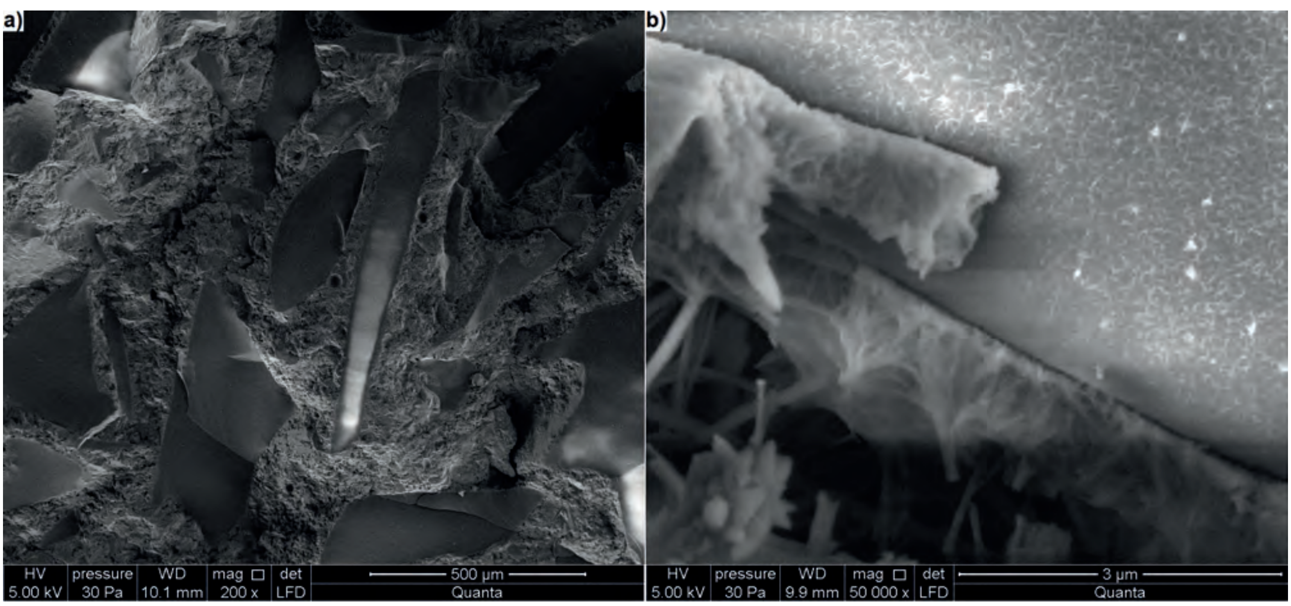

Fig. 7. Microstructure of mortar with glass cullet

It was also observed that no cracks or large pores can be seen between the glass and the cement paste, which demonstrates good bonding between the paste and aggregate (Fig. 7a and 7b). Only the accumulation of characteristic, plate-like portlandite crystals can be observed in this zone in some places. The glass particles themselves do not demonstrate any signs of major fracturing either. Their surfaces were usually smooth, but some were covered by products resembling C-S-H phase seeds, resulting from the pozzolanic reaction (Fig. 7b). These could be the products of an early phase of the alkali-silica reaction [3].

The non-reactivity of the tested waste glass is evidenced by the results of the testing of the mortar expansion in a 1M NaOH solution at 80°C, carried out in accordance with standard ASTM C 1260 (Fig. 8).

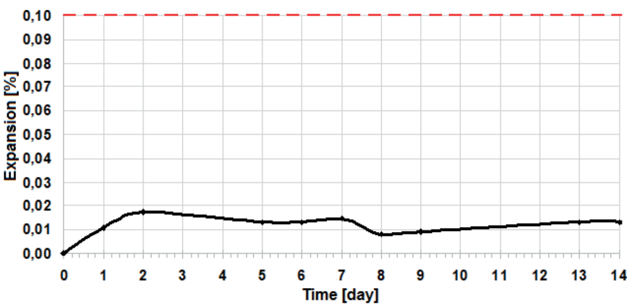

Fig. 8. Expansion of mortar with glass cullet acc. to ASTM C 1260 [16]

The achieved expansion did not exceed the threshold of 0.1%, which would suggest that a potentially deleterious alkali-silica reaction is taking place. These results are consistent with the results of the same tests carried out for brown glass by Najduchowska et al. [10]. Different results were, however, achieved for such glass by Jin et al. [21] and by Park and Lee [22]. In their paper, Park and Lee [22] demonstrated that brown glass is more susceptible to alkali-silica reactions and may exceed the 0.2% expansion threshold after 6 days of testing. Additionally, in a previous paper [12] it was established that the tested glass may cause significant mortar expansion in the case of long-term storage in an NaOH solution. Therefore, the non-reactivity of the tested glass applies only to tests performed during a standard-defined period, which should ensure that in real-life conditions a structure made of the tested material is suitably functional. But in conditions of extreme exposure to harmful factors, the tested glass could demonstrate reactivity. The effects of this can be clearly seen in a microscopic image of a 6-month-old mortar section (Fig. 9), which was initially used for testing in acc. with ASTM C 1260 [16] and was subsequently kept in water [12]. Extensive fracturing of the glass particles and single cracks running across the paste can be seen.

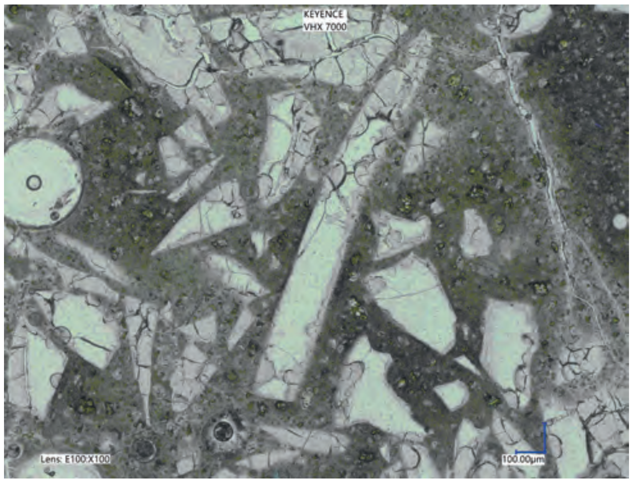

Fig. 9. Cracks in 6-month-old mortar

5. SUMMARY

During the conducted tests, the tested glass did not demonstrate any significant chemical activity. The tested brown packaging glass was not found to enter into a pozzolanic reaction or an alkali-silica reaction. Thus, the effect of glass on the properties of the tested cement composite was of a physical character.

It was found that the use of waste glass, both as a binder substitute and as an aggregate substitute, resulted in the reduction of the strength parameters of mortar. In the case of the replacement of cement with glass powder, this is related to the reduction of the binder content and is proportional to this reduction. In the case of the use of glass cullet, this reduction of parameters is related to the shape of their particles and differences in volumetric content resulting from the relatively low density of glass. It could also be caused by the mechanical properties of glass. Differences in volumetric content may also be responsible for the different effect of the use of glass powder and cullet on the consistency of mortar.

In view of previous testing, it must also be noted that non-reactive glass used during testing may actually demonstrate chemical activity in extreme conditions [12] or in the event of the presence of an activator in the mixture. Thus, the effect of different activating factors on its chemical properties can be tested during further research on the possibility of using non-reactive glass. Factors which may affect reactivity include particle size, and glass powder used for the tests (fraction 0-0.125 mm) was of a maximum particle size that, according to some sources [5], prevents the achievement of pozzolanic activity. Comparative tests of other types of glass should be performed because it is known that even packaging glass of a different colour can demonstrate different properties [10, 21-23].

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