13th International Conference
MODERN BUILDING MATERIALS, STRUCTURES AND TECHNIQUES

16–17 May 2019, Vilnius, Lithuania
Vilnius Gediminas Technical University

eISSN 2029-9915
eISBN 978-609-476-197-3

https://doi.org/10.3846/mbmst.2019.137

The effect of glass powder on physical and mechanical properties of hardened cement paste

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Abstract. The article analyses the effect of finely crushed glass on the properties of hardened cement paste. Materials used for the test: Portland cement CEM I 42.5 R, finely crushed glass (particle size ≤75 μm), and water. Seven compositions of cement paste mixes with different amounts of crushed glass (0%, 5%, 10%, 15%, 20%, 25%, 30%) added by weight of cement were designed. Compressive strength, density and ultrasonic pulse velocity of modified hardened cement paste with different content of crushed glass were measured in the tests. The test results revealed the increase of density, ultrasonic pulse velocity and compressive strength in specimens of hardened cement paste containing 5% and higher percentage of crushed glass after 7, 28 and 56 days of hardening. Microstructure tests revealed that crushed glass had an effect on the microstructure of hardened cement paste after 7 days of curing. X-ray analysis revealed the effect of crushed glass on the physical composition of hardened cement paste hydration products. Hardened cement paste containing 5% of crushed glass by weight of cement was found to have higher strength and density compared to unmodified cement paste.

Keywords: hardened cement paste, finely crushed glass, compressive strength, density, ultrasonic pulse velocity.

Introduction

All European countries face the accumulation of waste as one of the biggest problems. In Europe waste is usually collected and disposed in landfills. In Lithuania the biggest part of waste is disposed in landfills. The majority of landfills do not meet the environmental and sanitary-hygiene requirements. With more stringent environmental requirements and compliance to European Union directives the majority of landfills will have to be closed. In the future waste can be recycled and reused instead of disposing it. The economic and technological side of waste recycling requires special scientific knowledge. Integrated use of local raw materials along with different waste makes it possible to solve many environmental issues on the national level and have a positive effect on the European ecological balance. Numerous articles in scientific literature have revealed that a lot of waste and technogenic waste can be successfully used in the production of various building materials. Introduction of each waste into structural mixes is related to certain shortage of the specific raw material or the specificity of its introduction into the mix.

Glass is used in many forms as architectural glass, product containers, luminaries and other forms. Glass products have a limited lifetime. At the end of lifetime and with no recycling possibilities glass ends up in landfills. Glass is not biologically degradable, therefore it causes environmental problems (Shekhawat & Aggarwal, 2014).

Today various glass recycling concepts are being developed. Using waste glass in concrete manufacture is one of them. Industrial waste, such as ash, silica fume, are successfully used to improve concrete performance (Meyer, Egosi, & Andela, 2001).

There are numerous studies about using glass waste as concrete aggregates. Concrete mixes with the addition of crushed glass instead of sand have the same binding properties as concretes with natural sand. In order to obtain the same consistency of concrete mix with crushed glass as with natural sand more water is required due to the bigger amount of fine particles (up to 250 μm) in crushed glass. Concrete mixes with the addition of crushed glass instead of sand have almost the same volume of entrained air as concretes with natural sand. Chemical composition of sheet glass mainly consists of calcium oxide (CaO) and silica oxide (SiO_2). Fine particles of amorphous silica dioxide in crushed glass behave as active mineral addition in concrete and participate in cement hydration processes. This activity of crushed glass explains the increase in compressive strength of concrete with higher content of crushed glass in the mix. However, sheet glass also contains a sufficient amount of sodium oxide (Na_2O), which may cause alkali silica reaction in concrete. Research into alkali silica reaction in concrete modified with crushed glass addition is in progress. Concrete structure with crushed glass addition can be used only in the environment safe from alkali silica reaction. Alkali silica reaction reduces strength properties of concrete (Nagrockienė & Skripkiūnas, 2015; Byars, Morales, & Zhu, 2015).

Researchers have investigated the use of crushed glass in concrete manufacture. They noticed that pozzolanic activity is directly related to the fineness of glass particles. At present researchers mainly study the possibilities of using crushed glass in concrete. Crushed glass can be attributed to mineral additions. Various tests have proven that mineral additions used in concrete mix manufacture significantly improve the structure of concrete. This improvement is related to new compounds formed in pozzolanic reactions. The use of mineral additions reduces water demand by 15% compared to the mixes without additions. Water absorption also reduces (Topcu & Canbaz, 2004; Feldman, 1981; Manmohan & Metha, 1981; Sellevold, Bager, Klitgaard Jensen, & Knudsen, 1982; Marsh, Day, & Bonner, 1985; Cur, 1991; Tumidajski, 2006).

Various tests have proved that mineral additions, including crushed glass, reduce the expansion of concrete caused by alkali silica reaction (ASR). Researchers found (Samtur, 1974) that concrete specimens modified by crushed glass with particle size < 75 microns had lower expansion caused by ASR. Other authors (Shao, Lefort, Moras, & Rodriguez, 2000; Meyer, Baxter, & Jin, 1996) highlighted the size of crushed glass, which can have a positive effect on pozzolanic activity irrespective of alkali silica reaction. They claim that the expansion is lower when there are more fine particles. The newest studies revealed that glass powder obtained from bottles have pozzolanic properties and can be used as mineral additions (Meyer et al., 1996; Shi, Wu, Riefler, & Wang, 2005; Idir, Cyr, & Tagnit-Hamou, 2011; Zidol, 2009; Shayan & Xu, 2006). Pozzolanic activity increases with the decrease of particle size. The biggest interest lies in studying the effect of crushed sheet glass with the average particle size D50 = 13.67 microns and lower than 75 microns on mechanical properties of hardened cement paste (Aladdine, 2009; Kateb, 2009; Taha & Nounu, 2008; Idir, Cyr, & Tagnit-Hamou, 2010).

The aim of the paper is to analyse the effect of crushed glass on physical and mechanical properties of hardened cement paste.

Materials and test methods

Cement CEM 42.5 R complying with standard EN 197-1 requirements was used for the tests. Crushed glass from UAB Stikloporas with maximum grain size less than 75 μm was used. The crushed glass had the bulk density of 850 kg/m³, specific density of 2500 kg/m³, specific surface area of 2514 m²/g. Chemical properties of glass powder are presented in Table 1. Figure 1 illustrates crushed glass particle size distribution.

Table 1. Chemical composition of glass powder

Composition	SiO2	Na2O	CaO	MgO	Al2O3	P2O5	K2O	SO3	Fe2O3
% by mass	70%	14.20%	9.84%	3.74%	0.83%	0.55%	0.24%	0.23%	0.23%

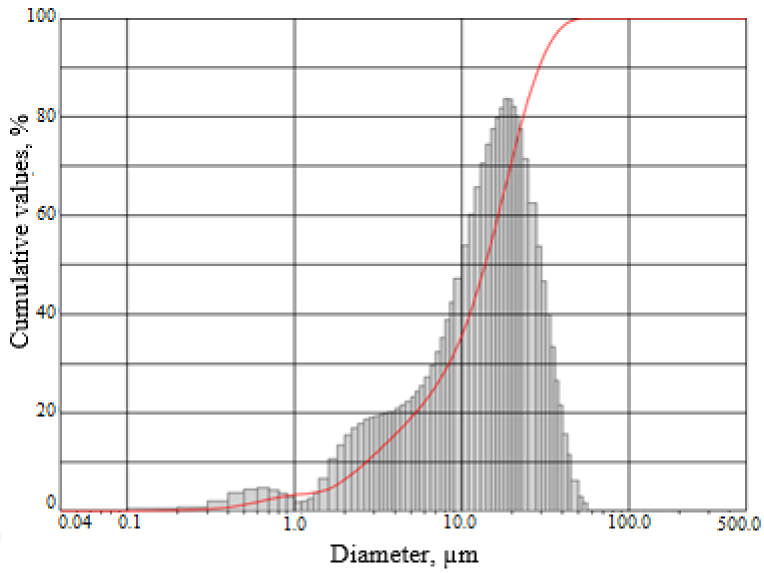

Figure 1. Crushed glass particle size distribution

The compositions of tested cement mixes are presented in Table 2. The mixes differed by the amount of crushed glass. W/C ratio in all mixes was the same, 0.39. Batches of all compositions were mixed in a mechanical mixer according to methodology prescribed by standard LST EN 196-1:2016 (Lietuvos standartizacijos departamentas, 2016). At first all materials were weighted and mixed manually. Afterwards, manually mixed materials were mechanically mixed in the mixer at low speed observing the duration of mixing cycles. After 30 s of low speed mixing water was added evenly during the next 30 s. After adding water the mixer was run for 30 s at the highest speed. After 90 s the mixer was stopped and during the next 30 s the paste was scraped from the walls and bottom of the mixer and placed in the centre of the mixer. Then the mixer was restarted at high speed and kept running for 30 s. Standard prismatic specimens 40×40×160 mm in size were cast from the prepared mix without compaction. The prisms were covered with plastic film and left for 24 hours to cure. After 24 hours the specimens were demoulded. The specimens were stored in the moist air cabined at 20±1.0 °C temperature.

Table 2. Mixing proportion of cement paste specimens with glass powders

Composition	I	II	III	IV	V	VI	VII
CEM I 42.5 R	69	64	59	54	49	44	39
Crushed glass %	0	5	10	15	20	25	30
Water (g/ml), %	31	31	31	31	31	31	31

Ultrasonic pulse velocity was measured is accordance with standard LST EN 12504-4:2004 (Lietuvos standartizacijos departamentas, 2004) requirements. The compressive strength was measured by means of Tinius Olsen H200KU press at 2400 N/s loading speed. XRD patterns of studied powders were measured using an X-ray diffractometer SmartLab (Rigaku) equipped with 9 kW rotating Cu anode X-ray tube. The measurements were performed using Bragg-Brentano geometry with graphite monochromator on the diffracted beam and a step scan mode with the step size of 0.02° (in 2θ scale) and counting time of 1s per step. The measurements were conducted in 2θ range 5–75°. Phase identification was performed using software package PDXL (Rigaku) and ICDD powder diffraction database PDF-4+ (2018 version).

Results and discussion

The effect of crushed glass on the density of modified hardened cement paste is presented in Figure 2. After 7, 28 and 56 days of hardening, density values were found to increase with higher content of crushed glass in the mix where up to 5% of cement was replaced by crushed glass. When crushed glass content in the mix was increased from 10% to 30% in 5% increments, density values went downwards compared to the control specimen. The highest density value of 1902 kg/m^3 was observed after 7 days of curing in specimens containing 5% of crushed glass. The difference of 33 kg/m^3 (1.77%) was observed compared to the control specimen's density value of 1866 kg/m^3. The lowest density value of 1816 kg/m^3 was obtained in specimens containing the highest 30% content of crushed glass. The difference compared to the control specimen's density value was 50 kg/m^3 (2.68%). After 28 and 56 days of curing the trend remained similar and the highest density values were observed in specimens where 5% of cement was replaced with crushed glass.

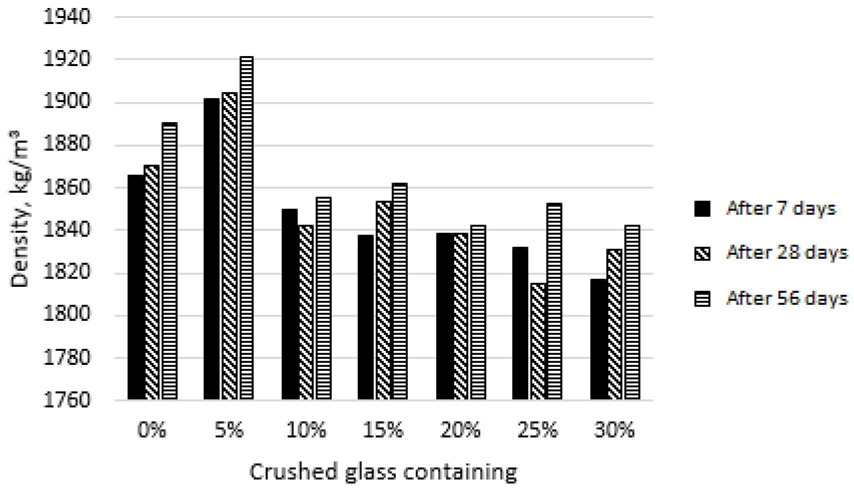

Figure 2. The effect of crushed glass on hardened cement paste density

Figure 3 illustrates the effect of crushed glass on the ultrasonic pulse velocity (UPV) in hardened cement paste specimens. After 7, 28 and 56 days of curing UPV values increased in hardened cement paste specimens containing 5% of crushed glass as follows: 3445 m/s after 7 days, 3554 m/s after 28 days and 3747 m/s after 56 days. Compared to the control specimen the increase in UPV value was 1.27%, 2.87% and 2.5%. Further increase in crushed glass content in concrete mix caused UPV value to decrease. Control specimen's UPV values after 7, 28 and 56 days of curing were 3401 m/s, 3452 m/s and 3650 m/s respectively.

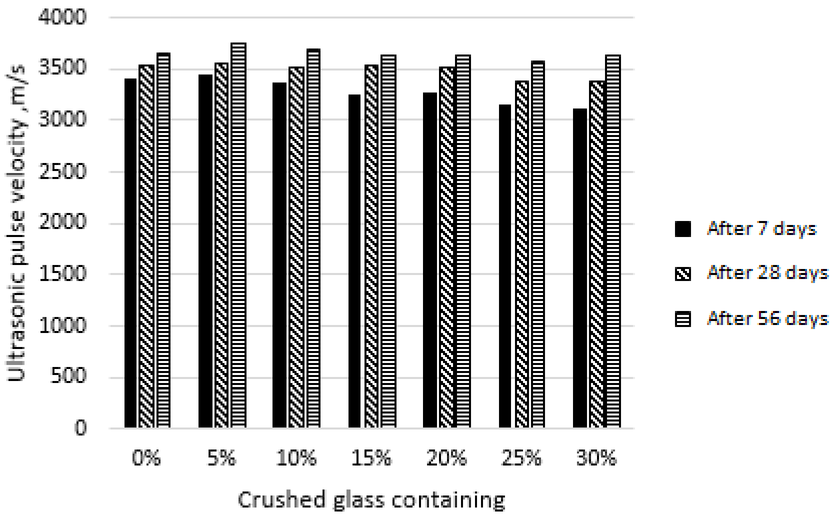

Figure 3. The effect of crushed glass on ultrasonic pulse velocity

Figure 4 illustrates the relationship between the compressive strength of hardened cement paste cured for 7, 28 and 56 days and crushed glass content. After 7, 28 and 56 days of curing the compressive strength values of the control specimen were 38.0 MPa, 39.9 MPa and 48.0 MPa respectively. The compressive strength values increased until up to 5% of cement was replaced with crushed glass. After 7, 28 and 56 days of curing the compressive strength values in the specimen containing 5% of crushed glass were 41 MPa, 44.2 MPa and 51.7 MPa respectively. Compared to the control specimen, the compressive strength value increased 7.32%, 9.5% and 7.16%. After 7, 28 and 56 days of curing the compressive strength decreased in specimens with higher than 5% content of crushed glass. After 7, 28 and 56 days of curing the lowest compressive strength values were obtained in the specimen containing 30% of crushed glass: 28.0 MPa, 30.8 MPa and 40.9 MPa respectively.

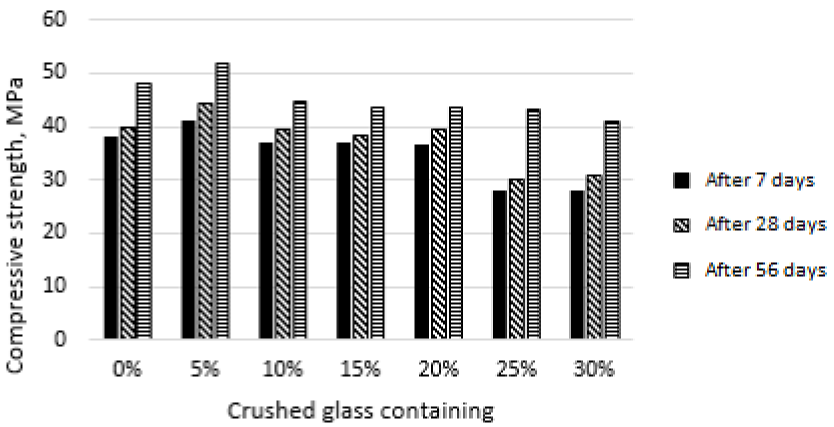

Figure 4. The effect of crushed glass on the compressive strength of hardened cement paste

X-ray diffraction analysis was done to investigate into the effect of crushed glass on the mineral structure of hardened cement paste. The mineral structure of control specimen and specimens with the lowest 5% and the highest 30 % limit content of crushed glass was examined.

The structure of hardened cement paste without crushed glass (control specimen) is presented in Figure 5. Cement paste without crushed glass is made of 62.75% portlandite, 33% of calcium carbonate, and calcium aluminium iron silicate hydroxide, sodium aluminium silicate hydroxide, larnite.

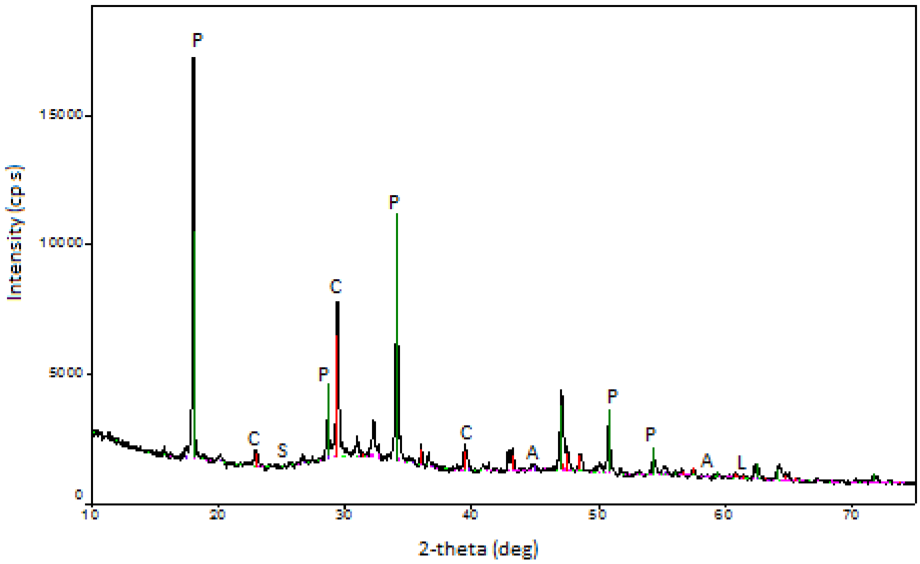

Figure 5. X-ray image of hardened cement paste without crushed glass: P – Portlandite; C – Calcium Carbonate; A – Calcium Aluminum Silicate Hydroxide; S – Sodium Aluminum Silicate Hydroxide; L – Larnite

X-ray analysis of hardened cement paste containing 5% of crushed glass (Figure 6) revealed the prevalence of portlandite in the total amount of 58.46%, i.e. 4.29% lower than the amount in the control specimen. Calcium carbonate amounted 36%, i.e. 3% more compared to the control specimen. The test specimen contained 5.4% of periclase that was absent in the control specimen. The remaining minerals were calcium aluminium iron silicate hydroxide, sodium aluminium silicate hydroxide.

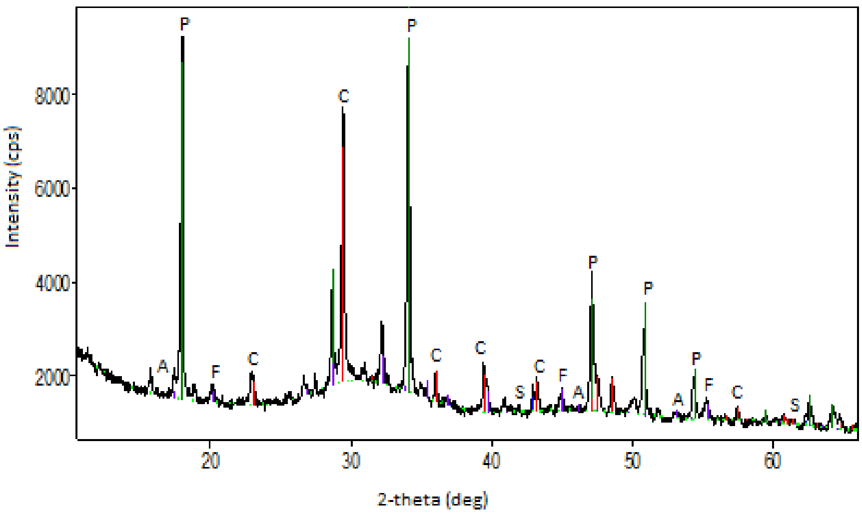

Figure 6. X-ray image of hardened cement paste with 5% of crushed glass: C – Calcium Carbonate; S – Sodium Aluminum Silicate Hydroxide; P – Periclase; F – Calcium Aluminum Iron silicate Hydroxide; A – Calcium Aluminum Silicate Hydroxide

X-ray image of hardened cement paste specimens with the highest tested content of 30% of crushed glass after 28 days of curing is presented in Figure 7. The image reveals the prevalence of portlandite making up 59%, i.e. 3.75% lower than the amount in the control specimen. Calcite makes up 22% or 11% less compared to the control specimen. There is also 10% of hatrurite, which was absent in the control specimen, and 5.8% of diopside, which had formed only when 30% of crushed glass was used in the mix. The remaining 3.2% is made of quartz. Apparently it is glass powder that had not reacted during the hydration process.

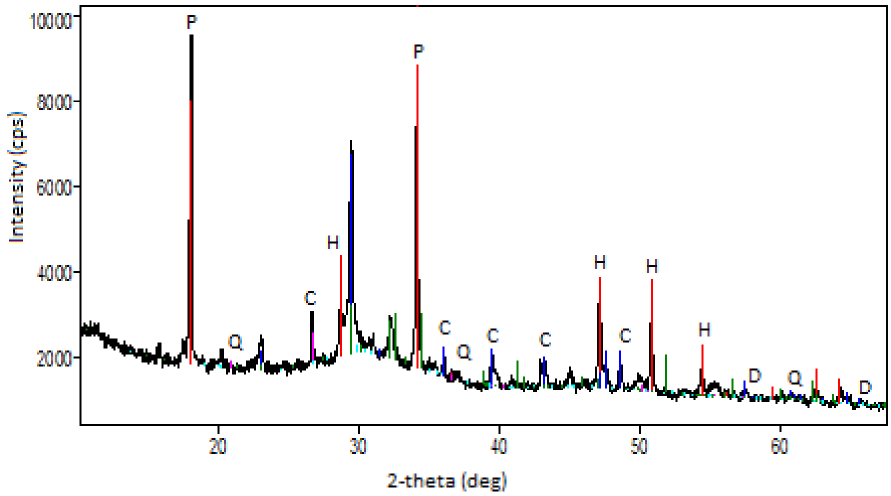

Figure 7. X-ray image of hardened cement paste with 30 % of crushed glass: C – Calcite; D – Dioposite; H – Hatrurite; Q – Quartz; P – Portlandite

Conclusions

1. Tests of hardened cement paste modified with crushed glass revealed that after 7, 28 and 56 days of hydration specimens where 5% of cement were replaced with crushed glass had the highest density values.
2. After 7, 28 and 56 days of curing UPV values increased in hardened cement paste specimens containing 5 % of crushed glass as follows: 3445 m/s after 7 days, 3554 m/s after 28 days and 3747 m/s after 56 days.
3. The compressive strength values increased until up to 5% of cement was replaced with crushed glass. After 7, 28 and 56 days of curing the compressive strength values in the specimen containing 5% of crushed glass were 41 MPa, 44.2 MPa and 51.7 MPa respectively. Compared to the control specimen, after 7, 28 and 56 days of curing the compressive strength value increased 7.32%, 9.5% and 7.16% respectively. With further increase of crushed glass content above 5%, the compressive strength decreased.
4. X-ray analysis revealed that a high portion of quartz (3.2%) had not reacted during the hydration process in specimens where 30% of cement was replaced with crushed glass.
5. Hardened cement paste modified with 5% of crushed glass demonstrated better physical and mechanical characteristics. There is also a positive economic effect as part of cement can be replaced with crushed glass.

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