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Lime-silica products based on waste packaging glass

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Abstract: Waste packaging glass with different chemical compositions were used to prepare lime-silicate products, a form of eco-friendly building materials. The percentages of glass, occurring in three colours: colourless, green and brown, were 33, 66 and 100 per cent by weight of quartz sand, which, along with lime, is the main component of silicate products. Compressive strength, bulk density and water adsorption were tested on autoclaved cylindrical specimens with a height and diameter of 25 mm. The results show that as the waste glass content of the autoclaved samples increases, the compressive strength and water adsorption increase, at the same time, the bulk density decreases. The chemical composition that determines the colour of the glass shows differences in the physical and chemical characteristics obtained.

Keywords: lime-silica products, waste glass, compressive strength

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Introduction

Technological progress and a consumer lifestyle over the last few decades have led to rapid increases in environmental pollution and the depletion of natural resources on which today's economy relies. The consequence of progress can be an economic and environmental crisis. On the one hand, alternatives to natural resources have to be found, while on the other hand, the problem of the enormous, ever-increasing volume of waste generated in households and industry has to be tackled.

Every year, cities produce more and more waste and the area available for landfill is decreasing. The production of glass consumes significant amounts of energy, as the melting of silica takes place at a high temperature and over a relatively long time (Chen et al., 2006). For example, in the production of container glass,

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the temperature must be maintained at 1500 °C for 24 hours and for flat glass for 72 hours. Producing 1 kg of flat glass uses about 17 MJ of fossil fuel energy and releases about 0.6 kg of CO_2 into the atmosphere (Olofinnade et al., 2007). Annual energy consumption for glass production in Europe exceeds 350 PJ, which is about 20 % of total industrial energy consumption (Schmitz et al., 2011). The efficient use of glass waste is becoming a priority issue.

A popular method of disposing of glass waste, due to its recyclability, is to re-use it in production technology. In this process, the waste must be carefully sorted, cleaned and melted (Guo et al., 2020). The different chemical compositions and properties, depending on the type of waste glass, affect the duration of the process and consequently, the energy consumption. The current level of glass recycling is not satisfactory. In 2018, approximately 130 million tonnes of glass were produced worldwide, of which only 21 % was recycled (Idir et al., 2011).

An alternative method of disposing of waste glass is to use it in the production of infrastructure materials such as concrete (Al-Zubaid et al., 2017; Černý et al., 2018; Idir et al., 2010) or autoclaved bricks (Stępień et al., 2020). Crushed waste glass can be used as a partial substitute for cement/lime, sand and/or coarse aggregates. The glass used for this type of material does not need to be heat-treated, resulting in lower energy consumption. The treatment of waste glass is greatly simplified and its safe disposal is increasing as the demand for building materials increases.

Waste glass, made of amorphous silica, is less stable, has higher solubility than the sand traditionally used as aggregate and is made of crystalline quartz, thus it can react more easily with the binder under hydrothermal conditions. In the literature, building materials (Chen et al., 2006; Corinadeldesi et al., 2005; Park et al., 2004; Shayan & Xu, 2006; Taha et al., 2008) are known to offer the possibility of reusing different types of glass with different chemical compositions. The type of reuse depends mainly on its particle size and its reactivity (Czapik et al., 2021). It is usually assumed that glass with a particle size of 0.038-0.3 mm can exhibit pozzolanic properties (Matos et al., 2012; Shao et al., 2000). However, due to the lack of clear conclusions from the use of different colours of waste packaging glass, especially in autoclaved materials, it is considered reasonable to undertake studies to indicate their influence on the physico-mechanical properties of autoclaved lime-silica products. The use of glass waste in the production of autoclaved lime-silica products will increase the options for the recycling of waste materials and also reduce the extraction of natural resources. The topic addressed is therefore geared towards the sustainable development of the European economy.

1. Materials and methods

1.1. Materials characterization

In accordance with standard (PN-EN 1008:2004), potable water was used as an ingredient in the lime-silica mixture and was not subject to additional testing.

Lime from the Sitkówka Trzuskawica A CRH Company (Poland) with a bulk density of 0.58 kg/dm^3 was used, meeting the requirements for quicklime used in the production of lime-silica products, as shown in Table 1.

Table 1. Chemical compositions and performance properties of lime (*own research*)

Chemical composition of lime	Requirements for lime	Lime used in the study
$CaO + MgO$	≥ 90 %	≥ 91 %
MgO	≤ 5 %	≤ 2 %
CO_2	≤ 4 %	≤ 3 %
SO_3	≤ 2 %	≤ 0.5 %

In this study, quartz sand was used with a 2.5-0.5 mm fraction equal to 19 % and a 0.5-0.05 mm fraction equal to 81 %. The density of the sand was 2650 kg/m^3. The sand used for testing included: SiO_2 = 97.59 %, Al_2O_3 = 1.16 %, $Na_2O + K_2O$ = = 0.76 %, CaO = 0.06 %, TiO_2 = 0.02 %, P_2O_5 = 0.02 %, MgO = 0.01 %. The sand met the quantitative guidelines for chemical composition (tested in accordance with standard (PN-EN 196-2:2013).

In this study, packaged waste glass, resulting from mechanical crushing from green and brown bottles, and glass from colourless jars, from household waste was used. The grain size was adapted to the distribution of the quartz sand fraction, as the aggregate exchange was done at 1:1 by weight. The chemical composition was performed according to standards: ISO (29581-2:2010) and PN-EN (196-2:2013) and is presented in Table 2.

Table 2. Chemical composition of packaging waste glass [%] (*own research*)

Chemical compositions	Colourless glass (WG)	Brown glass (BG)	Green glass (GG)
SiO_2	72.53	71.56	72.11
Na_2O	13.03	13.13	13.15
CaO	10.53	10.28	10.01
Al_2O_3	1.93	1.72	1.73
MgO	1.19	2.14	1.44
K_2O	0.36	0.47	0.57
SO_3	0.14	0.03	0.02
Fe_2O_3	0.08	0.41	0.43
TiO_2	0.07	0.11	0.14
SrO	0.05	0.02	0.04
ZrO_2	0.02	0.02	0.02
P_2O_5	0.01	0.01	0.01
Mn_2O_3	0.01	0.05	0.03
Cr_2O_3	0.00	0.04	0.25

1.2. Testing methods

Compressive strength was determined on six cylindrical samples of lime-sand products of the same series, with a height and diameter of 2.5 cm. The test was carried out using a Controls 50-C9030 hydraulic press 21 days after the autoclaving process, according to the guidelines set out in standard PN-EN (772-1+A1:2015). The samples were stored under laboratory conditions at room temperature prior to testing.

Volumetric density, which is the ratio of the mass of the dry material to its volume including the pores contained within it, was tested using the hydrostatic method, according to the calculation scheme described in Borek et al. (2022). The samples were dried at 103 °C to a constant mass. Cylindrical samples of autoclaved lime-sand products were used for the test. In each case, tests were carried out on 6 samples of the same batch. The arithmetic mean of the values obtained was taken as the result of the determination. The same samples were used for water absorption and open porosity tests. The determination of water absorption was carried out in accordance with standard PN-EN (772-21:2011).

1.3. Preparation of samples

Ten lime-sand mixtures were prepared. Samples were made according to the methodology described in articles Borek & Czapik and Borek et al. (2022). Table 3 shows the percentage and weight of waste container glass, quartz sand and lime for the individual experiments. The R designation was assigned to samples with the classic composition (reference samples). G33 samples with 33 % waste container glass were determined, followed by samples with 66 % waste container glass – G66 and G100 samples in which the quartz sand was completely replaced.

Table 3. Mass composition of mixtures modified with waste packaging glass (*own research*)

No sample	Share of waste glass		Share of sand		Share of lime	
	[%]	[g]	[%]	[g]	[%]	[g]
R	0.00	0.00	92.00	230.00	8.00	18.40
G33	30.36	75.90	61.64	154.10	8.00	18.40
G66	60.72	151.80	31.28	78.20	8.00	18.40
G100	92.00	230.00	0.00	0.00	8.00	18.40

2. Results and discussion

Regardless of the colour of the glass, the lime-silica samples show higher compressive strengths, relative to the R samples (3.81 MPa). Samples containing colourless waste glass show the highest compressive strength values, with the WG100 formulation having the best result of all those analysed. The average compressive strength of the WG100 samples is 10.95 MPa, which is 11.05 % and 22.90 % higher compared to the BG100 and GG100 samples, respectively (Fig. 1). This effect is due to the fact that clear glass is the most reactive and is the least doped with oxides compared to brown and green glass. Preliminary studies show that it is the most reactive glass, increasing the production of hydrated calcium silicates, which are responsible for the mechanical properties of the finished products. The lowest average result among the modified samples is shown by those with green waste glass GG33 = 4.93 MPa. Green glass is characterised by the highest content of modifying oxides, which can reduce the activity of the glass and break the bonds between the bonding elements, thus weakening them. Analysing the values obtained, it can also be seen that irrespective of the colour of the glass used, as the proportion of waste material increases at the expense of quartz sand in the sample, the compressive strength increases (e.g. the results for WG100 are 68 % and 110 % higher compared to those of WG66 and WG33).

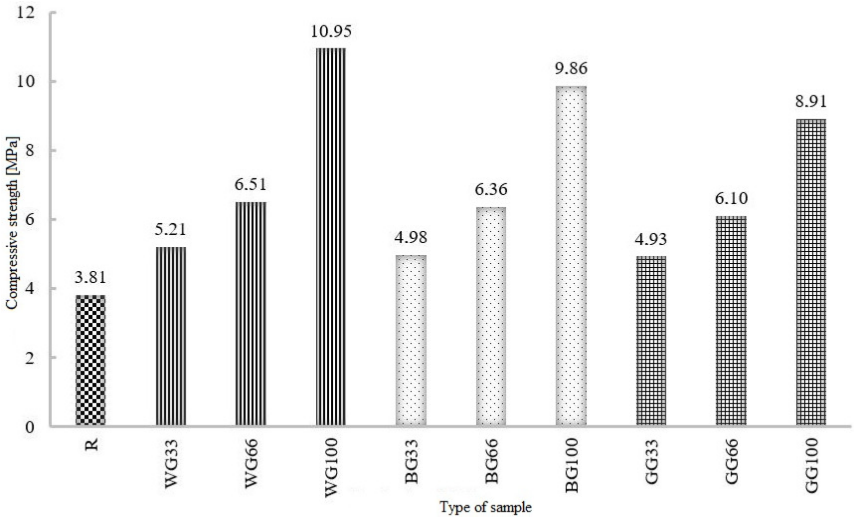

Fig. 1. Graphical representation of the average compressive strengths for the samples analysed (*own research*)

From the test results obtained, it can be seen that the volumetric density varies according to the glass colour used (Fig. 2). WG100 has the best result of all those analysed. The average volumetric density for WG100 is 1631 kg/m^3, which is 4.23 % and 10.58 % lower than the BG100 and GG100 samples, respectively. The volumetric density of the WG100 samples is also 16.66 % lower than that of the classic composition. The highest average result among the modified samples is shown by those with green waste glass GG33 = 1950 kg/m^3. However, irrespective of the glass colour, the lime-silica samples show lower volumetric density parameters, relative to the R samples (1957 kg/m^3). Firstly, this has to do with the use of more aggregates with a lower specific density relative to quartz sand, with the lowest specific density being found in colourless glasses (2479 kg/m^3). Secondly, the differences in the volumetric density of samples with clear, green and brown glass densities may be due to their different chemical properties. They may form different phases and microstructures, the determination of which is subject to further XRD and SEM EDS studies. Subsequently, the structure of the contact zone between the binder and the aggregate, as well as the reaction of the aggregate used with the binder, may also have an influence on the porosity of the silicate.

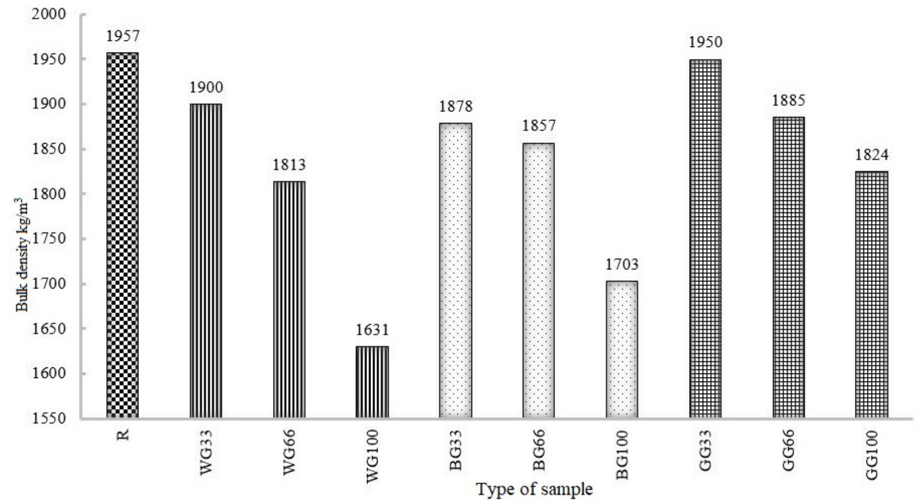

Fig. 2. Graphical representation of the average volumetric densities for the samples analysed (*own research*)

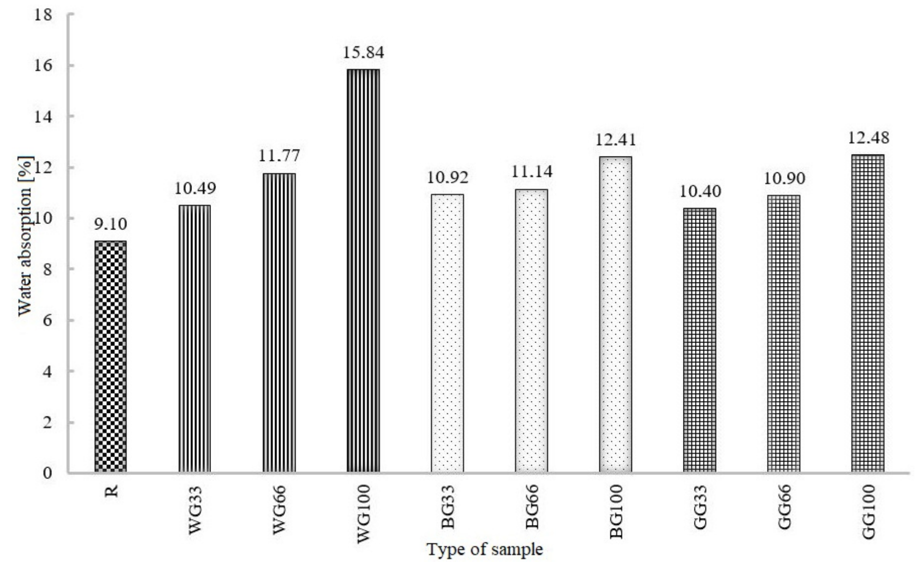

Fig. 3. Graphical representation of average water absorption for the samples analysed (*own research*)

From the results obtained, it can be seen that water absorption varies according to the glass colour used (Fig. 3). However, irrespective of the colour of the glass, the lime-silica samples show higher water absorption parameters compared to the R samples (9.10 %). Within the group of G33 and G66 modified samples, the samples with green glass show the lowest absorption. In the case of total replacement of quartz sand with waste glass, the lowest value of the analysed parameter is indicated by samples BG100 = 12.41 %. The results obtained are comparable with GG100 = = 12.48 %. The highest average water absorption is shown by samples WG100. This phenomenon may be related to the different microstructure produced by modification with glass of different chemical composition.

By analysing the values obtained, it can also be concluded that, irrespective of the colour of the glass used, water absorption increases with an increase in the proportion of waste material in the sample.

Conclusions

The results of testing the influence of packaging glass of different colours on the properties of autoclaved lime-silica products led to the following conclusions:

1. Irrespective of the glass colour used, there is an increase in compressive strength, with a decrease in bulk density and an increase in water absorption compared to samples with a classic composition.
2. As the content of waste glass increases in autoclaved samples, compressive strength and water absorption increase, while volume density decreases.
3. The complete replacement of quartz sand in the lime-silica samples with colourless waste glass (WG100) generates an increase in strength of ~187 % compared to samples of classic composition (R). The use of brown glass (BG) and green glass at 100 % aggregate weight increases the compressive strength by ~159 % and ~134 %, respectively, relative to the R samples.
4. The use of colourless glass at 100 % aggregate weight results in a 4.4 % and 11.8 % reduction in volumetric density relative to the BG100 and GG100 samples, respectively.
5. The use of brown wrapping glass as a replacement for quartz sand in the lime-silica samples has the least effect on increasing water absorption compared to GG and WG products. The average water absorption results for the BG100 samples show lower water absorption (by 0.6 % and by 27.6 %).

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