The Use of Waste Glass for Cement Production

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Abstract. The vast body of research conducted so far has focused on the use of waste glass as a partial replacement for cement or aggregate in the production of materials with cement matrix. This paper presents an alternative method of using glass waste for cement production. Grinding of previously burnt Portland clinker with glass cullet in green and white colours was used. The glass cullet was ground with Portland clinker in proportions of: 92.5% clinker and 7.5% green and white glass, 85% clinker and 15% green and white glass. Furthermore, pure cement was mixed with green and white glass fragmented in the disintegrator with the same proportions. This allowed for obtaining 8 series of cements (4 series with green glass and 4 series with white glass) and pure cement without waste glass. The compressive strength tests conducted after 2, 7 and 28 days made it possible to analyse the effect of the quantity and colour of waste glass and the method of its application (grinding with Portland clinker, mixing glass with pure cement) on the mechanical parameters of standard mortars. The highest mean compressive strength values after 2, 7 and 28 days were obtained for mortars made of cement coming from grinding of Portland clinker with 15% white glass. Furthermore, the following examinations were conducted: the beginning of the setting time and the degree of grinding of cements.

1. Introduction
Concrete is the most commonly used material in the construction sector, with the annual world production of cement, which is the main component of concrete composite, reaching about 4 billion tons. Cement is a mineral binder whose main component is Portland clinker. Burning of 1 tonne of Portland clinker in a rotary kiln releases approximately 900 - 950 kg of carbon dioxide depending on the fuel used. It is commonly known that currently produced cements contain not only Portland clinker, but also other ingredients with pozzolanic properties. These are additives that have binding and hydraulic properties such that the most expensive cement component, i.e. Portland clinker, can be reduced. Additives to cement can include: granulated blast furnace slag, silica dust, silica fly ash, natural and industrial pozzolana, lime fly ash, or burnt shale. These are additives which are formed from various industrial processes (e.g. iron ore smelting in a blast furnace, production of silicon in arc furnaces, combustion of hard and brown coal) and are their by-products (industrial waste). With their properties, they can be used in the cement industry and do not pose a problem with storage. Furthermore, they have an effect on the reduction of greenhouse gas emissions. This leads to obtaining the cement of CEM II to CEM V characterized by additional special properties that the Portland cement CEM I do not have.

For many years, research has been conducted to manage other production waste in the cement and concrete industry, e.g. rice husk ash, post-production ceramics or waste glass. Sodium-calcium glass usually contains about 70% SiO₂, 13-17% Na₂O and 10% CaO. High content of silica inspires the research on determination of the usefulness of this waste for cement and concrete production. However, alkalis (K₂O and Na₂O compounds) represent a problem, which may lead to a harmful
alkali-silica reaction (ASR), with its product being alkaline and silica gel, which increases the volume when the concrete becomes wet. However, in order for the alkali-silica reaction to take place, the reactive forms of silica must be present in the aggregate used for concrete while the concrete must be sufficiently wet. Furthermore, the research has shown that an addition to concrete in the form of finely ground glass does not always lead to the formation of a harmful alkaline-silica gel and can represent a partial replacement of cement in materials with cement matrix [1-4]. The addition of other materials such as silica fly ash, blast furnace slag, metakaolin or lithium compounds to concrete with ground waste glass also reduces the risk of ASR [5-6]. Moreover, it has been shown that the addition of waste glass in the form of finely ground powder does not contribute to the occurrence of ASR [7-8]. An extensive analysis of the use of waste glass in the cement and concrete industry was carried out by Shi and Zheng [6]. They considered that the use of glass waste as a partial substitute for aggregate slightly worsened the workability of concrete mixtures, leading in some cases to a decline of compressive strength and a decrease in frost resistance. According to [6], waste glass can be successfully used as a material rich in silica for cement production. The potential of waste glass (bottles) as a component for cement production was also confirmed by Chen et al. [9]. The bottles were supplied into the rotary kiln and burnt with a typical charge for the production of Portland clinker. The bottles were added in quantities of 1 and 1.77 tons per hour per 280-290 tons of the charge. It was found that the properties of cement obtained in this way did not differ from those of cement produced without glass cullet. The alkali content in clinker with the addition of waste glass was slightly higher than in the conventional clinker, but it did not exceed the permissible values, and the compressive strength of cement produced from Portland clinker with glass was less than 3% lower than in the conventional cement. Furthermore, there was no negative effect of burning Portland clinker with glass on the efficiency and operation of the rotary kiln.

A. Mafada Mators et al. [1] confirmed the usefulness of fine waste glass as a partial replacement for cement. These researchers performed tests by replacing 10 and 20% of cement in standard mortars with finely ground glass powder. Mortars with 10% addition of fine glass were characterized by high resistance to sulphates without reduction in compressive strength compared to mortars without glass. Higher alkali content was found in the mortars with fine glass, but the expansion of ASR was substantially reduced.

Glass cullet has been often used in research as a partial substitute for aggregate in a concrete mixture. Zainab et al. [10] replaced 10, 15 and 20% of sand with glass aggregate from bottles, jars and float glass. The addition of glass cullet deteriorated the workability of the concrete mix, but it positively influenced the mechanical properties of the tested concrete composites. Concrete with the addition of 20% glass cullet yielded by 4.23% higher mean compressive strength compared to control concrete without glass. The study also confirmed that partial replacement of sand with glass aggregate does not increase ASR. Corinaldesi et al. [11], Shayan and Xu [12] and Metwally [13] demonstrated that replacing the aggregate with glass cullet has a positive effect on the mechanical properties of materials with cement matrix, which allows for the fine glass waste to be approached as pozzolane material. It does not negatively affect the durability of the concrete composite, whereas the workability of concrete mixtures with waste glass can be compensated for by using greater amounts of plasticiser. Furthermore, Topçu et al. [14] proposed the use of 20% fly ash to reduce the risk of ASR in composites containing waste glass. In the study [15], fine cullet from white bottles was added to concrete in the amounts of 5 and 10% of cement mass. Concrete with addition of glass waste yielded compressive strength higher by 3.4% for addition of 10% glass cullet and 8.9% when adding 20% of this waste compared to the control concrete. Concrete obtained with addition of fine glass was characterized by: lower absorbability, higher frost resistance and lower water penetration depth compared to concrete without this addition. Topçu et al. [16] used glass waste for concrete as thick aggregate (4-16 mm). They replaced mineral aggregate with green sodium glass aggregate in the amounts of 15, 30, 45 and 60%. Concrete with a partial replacement of mineral aggregate with glass cullet yielded lower compressive strength. At 15% of glass aggregate, the mean decrease in strength was 8%, while at the maximum replacement of mineral aggregate with waste glass, i.e. 60%, the decrease was 49%. Taking into account the economic effects in the production of concrete of C16/20 class with the addition of thick glass aggregate in the amount of slightly more than 20%, the
researchers found that 1% savings can be achieved compared to the price of conventional concrete. The suitability of waste glass for concrete was confirmed by Terro [17]. Concrete with the addition of glass waste in the amount of 10% of aggregate mass was characterized by better mechanical properties at temperatures over 150oC. The mortars with 10, 20, 30, 40 and 50% of cement were also replaced with waste glass from LCD screens [18]. The most satisfactory mechanical properties and the highest resistance to sulphates were obtained by adding 10 and 20% of LCD screen waste. Satisfactory results were obtained by Khmiri et al. [19]. These researchers prepared 28 series of mortars with different contents of transparent and green waste glass. Tests confirmed that waste glass exhibits pozzolane activity in the presence of cement. Mortars obtained with addition of 80% of cement and 20% of waste glass with a diameter of up to 20 µm yielded comparable compressive strength to mortars obtained based on pure cement and binder in which 20% of cement was replaced by micro-silica.

2. Research Scope and Research Results

The literature review confirmed the possibility of using waste glass in the cement and concrete industry. The research focused on recycling of waste glass by using it as replacement for cement, sand or coarse aggregate in materials with cement matrix. In the study [9], waste glass was dosed to the rotary kiln during the burning of Portland clinker.

In this study, green and white waste glass from bottles was added to conventionally burnt Portland clinker and ground together in a laboratory mill with an additive that regulated the cement setting time (5% of cement mass). The chemical composition of glass is shown in Figure 1.

![Chemical composition of glass](image)

Figure 1. Chemical composition of glass

Both green (Z series) and white (B series) glass was added in the amounts of 7.5 and 15% clinker by weight. The quantitative compositions per 10 kg of cement obtained by grinding of clinker and glass together with the addition that delayed setting are shown in Table 1.

| Series | Green glass [kg] | White glass [kg] | Portland clinker [kg] | Anhydrite [kg] |
|--------|-----------------|-----------------|-----------------------|---------------|
|        | [%]             | [%]             | [%]                   | [%]           |
| Z7.5   | 0.71            | -               | 8.79                  | 0.5           |
|        | 7.1             | -               | 87.9                  | 5             |
| Z15    | 1.42            | -               | 8.08                  | 0.5           |
|        | 14.2            | -               | 80.8                  | 5             |
| B7.5   | -               | 0.71            | 8.79                  | 0.5           |
|        | -               | 7.1             | 87.9                  | 5             |
| B15    | -               | -               | 8.08                  | 0.5           |
|        | -               | -               | 80.8                  | 5             |

Further research involved addition of both types of waste glass into separately ground Portland clinker with the addition of anhydrite (pure cement). The glass was fragmented in the disintegrator (Figure 2) into glass flour and mixed with ground cement without the addition of glass. Grain composition of the glass fragmented in the disintegrator is shown in Table 2. The percentage
compositions of the tested cements (CZ series with green glass and CB series with white glass) are presented in Table 3.

![Figure 2. Disintegrator](image)

**Table 2.** Grain composition of fragmented waste glass

| Fraction [mm] | Green glass [%] | White glass [%] |
|---------------|-----------------|-----------------|
| 0.125-0.25    | 2               | 3               |
| 0.063-0.125   | 40              | 41              |
| 0-0.063       | 58              | 56              |

**Table 3.** Percentage composition of cement mixed with waste glass

| Series  | Green glass [%] | White glass [%] | Cemented ground without glass [%] |
|---------|-----------------|-----------------|-----------------------------------|
| CZ7,5   | 7.5             | -               | 92.5                              |
| CZ15    | 15              | -               | 85.0                              |
| CB7,5   | -               | 7.5             | 92.5                              |
| CB15    | -               | 15              | 85.0                              |

The following tests were conducted for all types of cement: compressive strength for standard mortar according to PN-EN196-1 [20], setting time according to PN-EN196-3 [21], degree of grinding by means of the Blaine air permeability method according to PN-EN196-6 [22]. Compressive strength tests were conducted after 2, 7 and 28 days of maturation of standard mortars. For comparison purposes, all studies were also performed for pure cement obtained from clinker grinding with anhydrite (C series). The results of determinations are presented in Table 4.

Normal mortar made of pure cement (control series C) yielded mean compressive strength of 36.8 MPa after 28 days. All other series of standard mortars obtained from cements with the addition of waste glass yielded higher strength values. The B15 series mortar obtained from cement from grinding of Portland clinker and white waste glass in the amount of 15% yielded the highest compressive strength. Its mean value was 41.2 MPa and was by 12% higher compared to the strength of pure cement. A high increase in strength for 28 days compared to the mortar made of pure cement was also obtained for the CB15 series, with 15% of white glass mixed with 85% of pure cement. Its mean value was 40.0 MPa, which is almost 9% higher compared to pure cement. It should be noted that after 7 days of maturing, the B15 series standard mortar had a higher compressive strength by as much as 17% compared to the C control series. Mortars obtained from green glass were characterised by slightly lower strength compared to mortars with similar compositions obtained from white glass. The degree
of grinding of all the obtained binders was similar and ranged between 3.190 and 3.310 cm²/g, which is a typical value for 32.5 class cements.

Table 4. Percentage composition of cement mixed with waste glass

| Series | Compressive strength [MPa] | Degree of grinding [cm²/g] |
|--------|---------------------------|---------------------------|
|        | after 2 days | after 7 days | after 28 days | Beginning of the setting time [min] |
| C 7.1  | 16.5        | 36.8        | 145          | 3260                      |
| Z7.5  | 7.5         | 17.8        | 38.3         | 140          | 3300                      |
| Z15   | 7.8         | 18.2        | 39.7         | 135          | 3280                      |
| B7.5  | 7.8         | 18.8        | 39.5         | 130          | 3290                      |
| B15   | 8.2         | 19.3        | 41.2         | 125          | 3310                      |
| CZ7.5 | 7.4         | 17.5        | 37.9         | 145          | 3210                      |
| CZ15  | 7.7         | 17.9        | 38.8         | 140          | 3190                      |
| CB7.5 | 7.6         | 18.0        | 39.0         | 130          | 3240                      |
| CB15  | 7.7         | 18.6        | 40.0         | 130          | 3200                      |

3. Conclusions
The following final conclusions can be drawn based on the research program:
- grinding of Portland clinker together with glass proved to be an alternative to management of this waste;
- standard mortars made of cements obtained from grinding of Portland clinker with waste glass had better mechanical properties. These cements were characterized by a faster rate of strength increase of 2 and 7 days, and higher standard strength (28 days) compared to the mortar made of pure cement;
- The largest increase in mean compression strength compared to pure cement mortar was obtained for a series in which Portland clinker was ground with 15% white glass. After 2 days, the mortar of this series yielded by 15.5%, after 14 days by 17% and after 28 days by 12% higher strength compared to the mortar obtained from pure cement;
- Cements obtained from grinding of Portland clinker together with green glass were characterized by good strength, but it was slightly lower compared to similar cements with white glass. Mortar made of cement obtained from grinding of Portland clinker together with green glass in the amount of 15% had higher strength after 2 and 7 days by 10%, and by 8% after 28 days compared to strength of mortar obtained from pure cement;
- mixing pure cement with fine waste glass also yields very satisfactory results. All series of mortars made of such cements yielded higher compressive strength after 2, 7 and 28 days compared to the strength of a mortar made of pure cement.
- All cements had similar beginnings of binding times,
- The degree of grinding for all cements is a typical size of cements of 32.5 class;
- Based on the tests, all cements were classified as 32.5N class.

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