Nonconventional Technologies Review
Romania, March, 2026

NON-CONVENTIONAL CONVERTING METHOD OF AN INERT RESIDUAL GLASSY MATERIAL INTO POZZOLANIC GLASS AS A TRADITIONAL CEMENT SUBSTITUTE TO PRODUCE STRENGTH-CONCRETE

Bogdan Valentin Paunescu[1], Lucian Paunescu[2], Adrian Ioana[3] and Enikö Volceanov[4]
[1] Consitrans SA, Bucharest, Romania, *Corresponding author,* pnscbogdan@yahoo.com
[2] National University of Science and Technology POLITEHNICA, Faculty of Materials Science and Engineering, Bucharest, Romania, ORCID No. 0000-0002-2467-5120 lucianpaunescu16@gmail.com
[3] National University of Science and Technology POLITEHNICA, Faculty of Materials Science and Engineering, Bucharest, Romania, ORCID No. 0000-0002-5993-8891 adyioana@gmail.com
[4] National University of Science and Technology POLITEHNICA, Faculty of Engineering in Foreign Language, Bucharest, Romania, ORCID No. 0000-0002-2020-476X evolceanov@yahoo.com

ABSTRACT: The current work concerns the technical feasibility of partially replacing Portland cement, the production of which creates huge environmental problems globally, with the widely available waste glass in the process of manufacturing construction concrete. The transformation of glass from an inert material into one with pozzolanic properties similar to those of cement by fine grinding of the glass represents a suitable method to achieve this objective. The experiment described in this paper allowed the replacement of cement with pozzolanic glass in proportions of up to 36 %. Using for the first time recycled amber glass from post-consumer drinking bottles together with cement as binders, common fine and coarse aggregates, sodium lignosulfonate as a water-reducing superplasticizer, and water, four concrete versions were made, in which the compressive strength was increased up to 49.8 MPa corresponding to the use of 36 % cement replacement and at the end of the 56-day curing process. Also, flexural strength reached a maximum value of 11.4 MPa under the same conditions.

KEYWORDS: residual glass, amber glass, Portland cement, pozzolanic properties, plasticizer, compressive strength.

1. INTRODUCTION

According to the literature [1], the energy consumption of manufacturing Portland cement as the main binding material in concrete has been estimated at 10-15 % of the energy consumed in the world industry, while up to 9 % of entire CO_2 emissions into the atmosphere, with negative effects on global overheating, are due to industrial cement production. On the other hand, concrete is a widely used material in this field due to its durability and strength properties, the requirement for this material growing continuously.

Under these conditions, the need to replace cement through other materials with almost similar cementitious and pozzolanic properties, but much cheaper and more environmentally friendly, has become a special priority at the global level. This type of materials adequate for replacing ordinary Portland cement have generally been identified and experimentally tested in the last decades, including coal fly ash, granulated blast furnace slag, rice husk ash, residual glass, silica fume, etc. [2].

Artificial pozzolans (such as pozzolanic glass) and natural pozzolans (such as volcanic rock pumice, perlite, volcanic ash, etc.) containing amorphous alumina-silicates capable to form C-S-H gel through the reaction with calcium hydroxide $Ca(OH)_2$ in the presence of water, are alternative opportunities to coal fly ash. Natural pozzolans have the ability to increase the durability and sustainability of concrete, but at the same time, they have variable physical-chemical properties, limited availability, and slow pozzolanic activity. Residual glass recovered from post-consumer drinking bottles has a relatively constant chemical composition, higher purity, and lower water requirement than fly ash and supplementary cementitious materials [2].

Several works [3, 4] have experimentally proven that inert glass waste ground to sizes below 300 μm exhibits pozzolanic features, increasing the mechanical strength of concrete due to that glass waste undergoes pozzolanic reactions with favourable effects in concrete, being able to substitute up to 30 % of the concrete cement and contributing to increasing the strength.

Also, it was found that pozzolanic glass with a grain size under 100 μm can exhibit a higher pozzolanic reactivity compared to that of fly ash after 90 curing days of concrete under conditions of a low degree of cement substitution [5]. Thus, CO_2 emissions into the atmosphere could be reduced by about 0.5 kg corresponding to 1 kg glass waste used in the mixture [6].

According to ASTM C125, a pozzolanic material contains silica or silica together with alumina, which can react with calcium hydroxide at ambient temperature when finely ground and in the presence of water. Thus, it facilitates the formation of C-S-H gel with cementitious properties. Supplementary cementitious materials are often used in the concrete mix as partial substitutes for cement. The common cement compounds, tricalcium silicate noted C_3S ($3CaO \cdot SiO_2$) and dicalcium silicate noted C_2S ($2CaO \cdot SiO_2$) chemically react with water (through the hydration process) to form $3CaO \cdot 2SiO_2 \cdot 3H_2O$ (i.e. C-S-H gel) and $Ca(OH)_2$. C-S-H gel is highly adhesive, with very low solubility, providing strength to the concrete. On the other hand, $Ca(OH)_2$ as a by-product of the reaction is water-soluble and is removed from the concrete, favouring a more porous character of the concrete along with a reduction in strength [2, 7].

In a pozzolanic reaction, supplementary cementitious materials react with $Ca(OH)_2$ to form an additional C-S-H gel, thus decreasing the entire amount of cement required to generate the same amount of C-S-H gel. The consequence is decreasing CO_2 emissions in cement manufacturing, improvement of long-term durability due to reduction of permeability and increase of resistance to chemical attack.

The mechanism of the pozzolanic reaction of C-S-H gel formation is presented in the paper [2], including the following stages:

$$2C_3S + 6H \rightarrow C_3S_2H_3 + 3Ca(OH)_2 \quad (1)$$

$$2C_2S + 4H \rightarrow C_3S_2H_3 + Ca(OH)_2 \quad (2)$$

$$\text{Pozzolan} + Ca(OH)_2 + H_2O \rightarrow \text{C-S-H (gel)} \quad (3)$$

The main differences identified between the cement hydration reaction (called primary hydration) and the pozzolanic reaction (called secondary hydration) are the reactants and the reaction rate. Primary hydration is initiated immediately after the introduction of water into the cement mass, allowing an early increase in the mechanical strength of concrete. The pozzolanic reaction begins to develop after the by-product of cement hydration, i.e. $Ca(OH)_2$ has been generated, this constituting an essential reactant for the secondary hydration process. The pozzolanic reaction has a slower development rate and it continues to operate depending on the $Ca(OH)_2$ quantity resulting from the primary hydration [2].

According to the literature [7], pozzolanic materials exist in nature in the form of volcanic origin materials as well as some clay minerals. Another category of pozzolans comes from processing clays and shales (such as fly ash, rice husk ash, and silica fume). The last category includes materials resulting from industrial processes such as granulated blast furnace slag and recycled glass, which obtain suitable characteristics after their grinding into a fine powder.

Until recently, beverage bottles were thrown into landfills without being recycled due to a lack of economic motivation. Because glass is generally a non-biodegradable material, its storage in landfills is not a sustainable operation in terms of environmental protection. Recently, it has been found that finely ground glass (under 150 μm) acquires pozzolanic features, being able to be used as a cement replacer (between 15-30 % of the cement mass). Compression resistance, but also durability, showed that 30 % would be the optimal level of cement replacement [1].

The chemical composition of pozzolans used in the manufacture of concrete (mainly containing silicon, aluminum as well as iron, calcium, magnesium, potassium, and sodium) can be affected by the nature of raw materials. In cementitious systems, the performance of pozzolanic materials is directly influenced by the amounts of these chemical components, which differ from case to case. All pozzolans contain large amounts of Si and Al, except for silica fume, which has a predominant proportion of silicon [2].

Ground glass pozzolan has a much lower percentage of SiO_2 (70-74%) than silica fume, but exceeds the pozzolanic reactivity values of other widely used pozzolans (fly ash, metakaolin, and granulated slag) due to its high SiO_2 content. With a higher silicon content, silica is more reactive, producing additional C-S-H gel during secondary hydration. When ground glass pozzolan is used as additional cementitious material, its reactivity leads to obtain better mechanical strength. The kinetics of the pozzolanic reaction and the ability of the material to react with $Ca(OH)_2$ during hydration are influenced by particle size, specific surface area, curing temperature, and chemical composition. Different types of glass (soda-lime glass, borosilicate glass, or tempered glass) exhibit widely varying reactivities [2].

Very high pozzolanic reactivity is achieved in the case of silica fume containing very high SiO_2 proportion. The ultra-fine particle size of this material is also another peculiarity that favours the rapid reaction with $Ca(OH)_2$ producing a lot of C-S-H gel and consequently, improving the mechanical performance and durability of concrete [8, 9].

The use of recycled glass in construction concrete has recently shown promising results, the demand for concrete in civil infrastructure being very high. So far, there is no real consensus among researchers on effects of residual glass in concrete. In the paper [10], an analysis is carried out aiming to resolve this controversy. Data on properties of fresh concrete, compression strength, durability, heat and electrical properties as well as the microstructure of several concrete samples using various types of residual glass were taken into consideration: soda-lime glass, cathode ray tube glass, lead glass, and borosilicate glass. The effect of glass on properties of fresh concrete was investigated taking into account the size of the glass grain, its chemical content, and its morphology. Also, it was found that the appropriate use of glass improves flowability, mechanical strength, permeability, and freezing-thawing resistance of concrete.

The possibility of using ground residual glass as a fine aggregate for construction concrete or asphalt has also been investigated in the last 5-6 decades, but this technology has not yet been fully assimilated due to the aggressiveness of the alkali-silica expansion reaction in concrete incorporating glass [11]. However, various recent analyses presented in the literature allow the conclusion that there is a real potential for using ground glass as a fine aggregate in construction materials. The mentioned work considers that more in-depth research is needed to clarify the controversial aspects on the properties of concrete using residual glass as a fine aggregate as well as ultra-light fibre reinforced concrete containing expanded residual glass.

According to literature data [9], the use of recycled glass in concrete can have both advantages and disadvantages. Potential advantages could be: improved impermeability, limiting the alkali-silica reaction, improving tensile strength, obtaining pozzolanic properties, increasing environmental protection through reducing landfills for glass, conserving natural resources, reducing CO_2 emissions, and reducing energy consumption. Possible disadvantages include: decreasing compression strength, affecting the workability of fresh concrete when glass is used as fine aggregate, increasing porosity, and affecting concrete performance due to the quality variation of recycled glass.

Waste glass can be used as a partial replacement for aggregates (fine and/or coarse) in concrete. Also, glass can be added to concrete by partially replacing any component of the mixture in different forms: powdered or crushed together with/without additives or plasticizers. The paper [12] investigated possibilities and effects of using glass as a partial replacement in concrete. The results showed that the introduction of recycled glass powder into the concrete manufacturing mixture would be the most appropriate method of cement substitution increasing the compressive strength, flexural strength, workability, and tensile strength of concrete. Partial substitution of fine aggregate by 20 % with glass powder leads to obtaining the maximum compression strength. Also, concrete containing glass powder has proven to be more economical and more environmentally friendly compared to conventional concrete.

Recent research has experimentally demonstrated that ground glass waste can be used as a pozzolanic material in concrete, improving its strength and durability [13]. Fine grinding of glass is the technical condition for obtaining adequate pozzolanic properties as a result of its reaction with $Ca(OH)_2$ in cement and the formation of additional cementitious compounds similar to other known pozzolans as fly ash or silica fume. The usual requirement of Portland cement is thus reduced, leading to diminishing the carbon footprint of the production process. Results showed that waste glass powder (optimal ratio of 20 %) with particle sizes in the range of 20-44 μm ensures higher suspension fluidity than reference samples and the suspension manifested better cohesion and water retention performance. When the particle size was between 44-150 μm, the compression strength of the blended mortar had lower values compared to the reference samples for all curing times. Using the optimal range of glass waste size (20-44 μm) led to lower strength values for early curing time (only 7 days), but increased by 3.5 % and 9 % after 28 and 90 curing days, respectively. Decreasing the glass grain size under 20 μm did not significantly increase the compression strength.

Although widely available in the world, especially in the form of packaging and window glass, glass products have a short lifespan, after which they become waste. The non-biodegradable peculiarity of waste glass makes it difficult to store in landfills, requiring its recycling and use in the form of other products with newly created value. One of the most viable applications of glass waste is based on the pozzolanic properties of finely ground glass used in the manufacture of construction concrete. The work

[14] aimed to investigate the behaviour of recycled pozzolanic glass applied as a partial cement replacement in this field. Concrete samples with 15-30 % cement replacement were tested. Glass powder with a grain size between 100-150 µm, having an adequate pozzolanic character, chemically reacts with lime in the early way of hydration, forming the additional C-S-H gel and contributing to more intense densification of the cement and increasing the durability of the concrete. The strength of concrete made with glass waste powder was determined to be slightly higher compared to the strength of concrete made with fly ash.

According to [15], the major applications of glass waste were oriented towards the construction sector, where residual glass was used as a construction material. The experiment aimed at using glass waste powder instead of fine and coarse aggregates in concrete. The results showed that the use of glass waste powder in the concrete composition through partially reducing the aggregate content under 10 % allows to obtain desired strength values after 28 curing days. On the other hand, values of replacing aggregates with glass waste between 15-20 % lead to lower strength values.

Another option for using glass waste in making concrete was presented in [16]. The optimal technical solution resulting from the mentioned experiment was the addition of glass waste fine powder into the mix through partial replacement of Portland cement as well as the use (up to 20 %) of ground glass as coarse aggregate. The effect of applying this method was to increase the compression, flexure, and breaking resistances. For glass addition above 20 %, the strength and durability of concrete decreased.

In the work [17] is shown that the chemical and mineralogical composition as well as the size of residual glass particles, material ratios in the mix, the activation, and peculiarities of the curing process are the main parameters that can influence the behaviour of the glass powder dissolution and the pozzolanic reactivity between the fine glass powder and other components in the concrete and implicitly, properties of the final product. Effects on the pozzolanic reactivity and filler are the most important consequences of reducing the density and porosity of residual glass particles in cement-based concrete. The concrete density of varies depending on the fineness, quantity, and type of residual glass. In the paper [17], an important increase in the concrete density containing up to 10 % cement replacement with glass powder is shown. An improvement in the concrete density using 20 % glass with grain size between 0.8-110 µm was highlighted in [18].

Numerous other works were focused on research on partial replacing the Portland cement with fine ground residual glass to obtain high technical performance of concrete. The paper [19] identified the optimal level of replacing the cement with glass powder at 10 %. By measuring the values of strength and hydration, the finely ground glass ability to improve the concrete durability was determined. Omran et al. [20] determined the mechanical and durability characteristics of concrete due to the use of glass powder as a cement substitute in the ratio of 20 %. It was experimentally found that glass powder reduced the early strength (after 7 days), but allowed the strength to increase after 91 days compared to the reference concrete. Also, it contributed to improving the resistance to repeated freeze-thaw cycles. The work [21] reported that the concrete containing glass powder as a partial cement replacer had satisfactory performances in terms of drying contraction and alkaline reactivity. Also, the glass contributed to reduce the concrete penetrability by chloride ions. Du and Tan have observed in their paper [22] that the concrete containing cement replaced with glass in ratios of 15 and 30 % had the highest growing of strength and consequently, the lowest porosity. In addition, reductions of over 77 % of water penetration depth, sorptivity, heat conductivity, chloride ion diffusion, and migration coefficient in cement-based concrete having cement replaced by glass in a ratio of 60 %. Other work published in the literature [23], reported that the glass ground at a relatively fine granulation influences the cement paste structure creating the growing tendency of its compactness and to reduce porosity. It has been experimentally found that an optimal ratio of 40 % glass powder has the ability to improve the compression strength of mortars [24].

The paper [25] investigated the opportunity of using ground glass waste as a partial replacement for Portland cement in the concrete mix. Starting from the recent discovery that glass powder acquires pozzolanic properties almost similar to those of ordinary cement, the mentioned paper describes the results of testing cement replacement in weight proportions between 0-25 %, leading to improved strength after the curing process. It was found that a 20 % cement replacement could be the optimal solution at 90 curing days in terms of profitability and environmental protection.

Another method of applying residual glass was its incorporation into high-performance geopolymer concrete [26]. Recycled glass replaced fine sand in ratios between 0-22.5 %. The prepared mixtures were introduced into solutions of H_2SO_4 (2 %) and $MgSO_4$ (5 %) respectively, and then were heated at temperatures between 200-800 °C for 1.5 hours. The results showed that the flowability of fresh mixture was increased by the glass content. The compression strength decreased from 126 to 121 MPa in the case of replacing the sand with 22.5 % residual glass and curing at room temperature. The samples immersed in the $MgSO_4$ solution had a strength loss of 5.3 % after 120 days, while the strength loss of samples immersed in H_2SO_4 represented 1.16 %. Mixtures incorporating residual glass had better thermal stability compared to the reference concrete.

A research team including authors of the current paper has conducted scientific investigations on the use of recycled post-consumer green drinking bottles as a partial replacement for fly ash in a geopolymer concrete [27]. The experimental results showed that the optimal solution for growing the compression and flexural strength of geopolymer concrete after both 7 days and 28 days of curing process at ambient temperature is the replacement of 18 % of the fly ash content of the concrete mix with recycled glass. Compression strength registered values of 34.8 MPa (after 7 days) and 46.0 MPa (after 28 days), while flexural strength reached 5.9 and 8.9 MPa respectively, after the same durations of the curing process.

The current work presented below aimed at the manufacture of a fly ash-based geopolymer concrete using the partial replacement method of Portland cement by adopting recycled post-consumer amber drinking bottle with grain size in the range of 10-55 µm.

2. METHODS AND MATERIALS

2. Methods

Amber glass post-consumer packaging can be used to manufacture geopolymer concrete, offering an alternative solution to traditional cement-based concrete. Recently, it has been recognized that glass converted into a fine powder has the ability to act as a precursor material or as a fine aggregate in the geopolymer mixture, largely replacing cement or natural aggregates. Thus, the dependence on natural resources is reduced and non-biodegradable waste is prevented from being disposed of in landfills, as is the case with residual glass [17].

In order to achieve the recycling of used glass, the influence of this waste on the rheological properties of cement paste and concrete was studied. The results showed that, in the case of preparing cement in suspension form, by increasing the amount of glass powder as a replacement material in the mixture (in proportions of 0-20 wt. %), the viscosity of the suspension gradually increases, while the yield stress decreases. The slight increase in the superplasticizer amount used as a water-reducing agent leads to a decrease in the viscosity and yield stress of the cement suspension. The rheological properties of fresh concrete changed after the addition of glass powder, in the direction that the viscosity of the concrete increased and the yield stress decreased after about one hour, according to [28].

The concrete workability, i.e. the ease of working with fresh concrete, is usually investigated by a slump. Thus, the fluidity and consistency of the mixture are determined by measuring the vertical settlement of the concrete sample after removing the conical mould [2]. Flow slump under conditions of varying the proportion of glass waste as a cement substitute between 0-30 wt. % has led to significant differences between the results of several researchers around the world. Thus, some authors have reported increases between 36-83 % of the slump value for 20 wt. % replacement of cement with waste glass. According to other authors, decreases between 19-30 % of the slump value were found. In the paper [28], the authors found that the slump value could gradually increase to 18 % in the case of 20 wt. % cement replacement, followed by a gradual decrease up to the level of cement replacement with glass powder of 40 wt. %.

Within the adopted method of preparing fly ash-based concrete in which the initial Portland cement was partially replaced with recycled residual glass from post-consumer amber drinking bottle, making this waste suitable to substitute the traditional technological role of Portland cement following its partial replacement. The method was based on the ability of commercial glass (soda-lime glass type) to turn through fine grinding from an inert material into one with pozzolanic characteristics almost similar to those of Portland cement. The method applied in this experiment is economical in energy terms, as high temperatures are not required.

The steps of concrete preparation included firstly grinding and mixing coarse aggregate (stone gravel) with fine aggregate (river sand). The appropriate sizes of the two aggregate types were 5-18 mm corresponding to coarse aggregate and under 2.5 mm corresponding to the sand. The recycled glass was ground to a grain size below 100 µm and mixed with the CEM I cement type in a separate container from the one containing aggregate. The cement-glass powder mixture was added to the aggregate mixture mass. The required amount of water, determined from the water/binder ratio with the preset value of 0.48, was also added and mixing was carried out for 6 min. After mixing was completed, the workability of the fresh concrete was measured by the slump test. In all versions of the glass powder addition, the slump values of the fresh concrete had to fall within the recommended limits of 100-125 [2]. The fresh material thus prepared was poured into metal moulds kept in a room with controlled humidity of 75-80 % for 24 hours. The hardened concrete samples removed from the moulds were stored in a room for the curing process for a maximum of 28 days before testing the strength characteristics.

2.2 Materials

The list of materials adopted to carry out the experiment contained: cement (CEM I type), amber glass powder recycled from post-consumer drinking bottle, river sand as fine aggregate, stone gravel as coarse aggregate, sodium lignosulfonate as a superplasticizer, and water.

CEM I cement type from the Portland cement group is composed mainly of Portland clinker (95-100 %) and a maximum of 5 % other substances. It is often used in high-performance concrete applications.

Amber glass powder was recovered through post-consumer drinking bottle recycling. Among the coloured commercial glass, amber glass has the highest alumina content (6.35 %) and also a sufficiently high silica content (70.66 %) [2], emphasizing the alumina-silicate character of the waste. Also, fine grinding of this glass waste (under 100 µm) contributed to developing pozzolanic properties of the powder, necessary to be suitable for partial substitution of Portland cement in the concrete manufacturing process.

River sand is a commonly used and readily available natural source of fine aggregate, known for its well-rounded particles, good workability, and uniform gradation. Bulk density of river sand is in the range of 1.64-1.78 g·cm^{-3} [30]. The chosen size of the sand grains after grinding was below 2.5 mm.

Stone gravel represented the coarse aggregate type adopted in this experiment. Gravel, a naturally available aggregate composed of rounded stones, is a common and effective choice for coarse aggregate in concrete making. It provides volume and stability to the concrete mix, enhancing its load-bearing capacity and reducing shrinkage. Gravel, typically ranging from 4.75 mm to 38 mm, is combined with the cement paste to create a strong and durable composite [31]. In the current experiment, the gravel dimension range was selected between 5-18 mm.

Sodium lignosulfonate ($C_{20}H_{24}Na_2O_{10}S_2$) is a type of water-reducing agent, also known as a superplasticizer, used in concrete to improve its workability and strength. These agents work by dispersing cement particles in a concrete mix, allowing a decrease of water required amount, maintaining or even increasing the desired consistency and strength. Lignosulfonates are chemicals derived from lignin, which is found in the plant wood. Industrially, they are extracted during the sulphite pulping process in the paper manufacturing. The sodium lignosulfonate used in the experiment originated in China. Its usual dosage is on average 0.25 % of the binder quantity.

Four experimental concrete variants prepared by partially substituting Portland cement with amber glass powder recycled from post-consumer drinking bottle and using the other materials and additives mentioned above were made and tested. The dosages of the starting mixture components are shown in Table 1 corresponding to each variant.

Table 1. Composition of experimental concrete variants

Composition	Variant 1 (kg·m^{-3})	Variant 2 (kg·m^{-3})	Variant 3 (kg·m^{-3})	Variant 4 (kg·m^{-3})
CEM I cement type	450	396	342	288
Amber glass powder (under 100 µm)	- (0 %)	54 (12 %)	108 (24 %)	162 (36 %)
River sand (under 2.5 mm)	630	630	630	630
Gravel (between 5-18 mm)	1014	1014	1014	1014
Sodium lignosulfonate	1.2	1.2	1.2	1.2
Water	216	216	216	216

According to Table 1, the proportion of cement replacement with amber glass powder varied between 0-36 %, increasing to 162 kg·m^{-3}, while the amount of Portland cement was reduced to 288 kg·m^{-3}. Unlike the experimental parameters used in [25], the current experiment increased the maximum level of cement replacement with glass powder up to

36 %. In addition, sodium lignosulfonate was chosen as a wood-based superplasticizer, cheaper than other types commonly used to reduce water requirements. On the other hand, we have no information about the use of amber glass waste as a substitute for cement in the concrete manufacturing process, so that this application may also constitute an originality element of the work.

2.3 Investigation methods for determining concrete features

Workability was measured using Abram's cone (SR EN 12350-2:2009). The density was determined based on ASTM C138/C138M-17a, while ASTM C642:2022 was the standard used to measure the hardened concrete porosity. The compression strength was investigated through the method provided by BS EN 12390-3:2009 on the cubic sample, while the flexural strength was measured on the rectangular specimen by applying the third-point loading test (ASTM C78/C78M;2022). Modulus of elasticity was measured according to ASTM C469-02e1. The water uptake of cement-based concrete was determined using the standard method ASTM C1585:2020 and the microstructural peculiarities of concrete samples were identified with Biological Microscope model MT5000.

3. RESULTS AND DISCUSSION

3.1 Results

Applying the Abram's cone test for slump flow has demonstrated the acceptably level of the fresh concrete workability, under the conditions that the slump flow values fell within the range of 112-119 mm, according to Table 2.

Table 2. Results of Abram's cone test for slump flow

Variant	**1**	**2**	**3**	**4**
Slump flow (mm)	115	119	112	116

The physical appearance of concrete specimens prepared by partial replacement of cement with amber residual glass are exhibited in Figure 1.

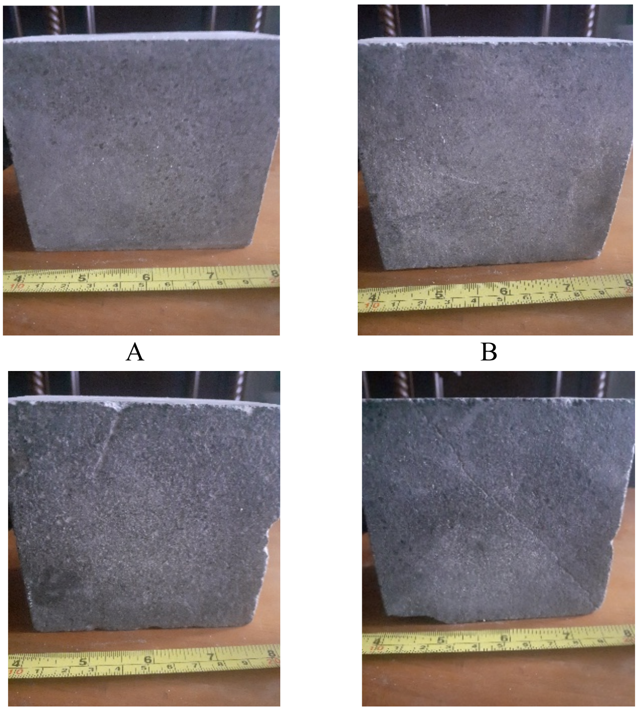
A B C D

Figure 1. Physical appearance of concrete specimens A – variant 1; B – variant 2; C – variant 3; D – variant 4.

The principal features of concrete samples made in this experiment are shown in Table 3.

Table 3. Principal features of concrete samples

Feature	**Variant 1**	**Variant 2**	**Variant 3**	**Variant 4**
Density (kg·m^{-3})	2246	2238	2220	2213
Porosity (%)	15.8	16.8	18.0	19.3
Compressive strength				
- after 7 days	27.8	31.8	38.2	42.6
- after 28 days	35.8	37.9	42.9	47.1
- after 56 days	38.4	40.0	45.7	49.8
Flexural strength				
- after 7 days	4.8	6.0	6.9	7.8
- after 28 days	7.3	7.9	8.7	9.8
- after 56 days	9.0	9.6	10.8	11.4
Modulus of elasticity (GPa)	30.1	28.5	26.6	25.2
Water uptake (vol. %)	3.5	3.5	3.3	3.6

Since the density of Portland cement is slightly higher compared to that of recycled commercially glass, the density of concrete, including higher proportions of cement in all experimental variants and increasing glass amounts has decreasing values from 2246 to 2213 kg·m^{-3}. On the contrary, porosity tends to increase within the limits of 15.8-19.3 %.

Compressive and flexural strength was determined both at early time of curing (7 days) as well as after 28 and respectively, 56 days, observing an appreciable increase throughout the entire duration of the free curing process of the concrete samples.

The influence of the percentage growing of glass powder (between 0-36 wt. %) in the total amount of concrete binder (cement + pozzolanic glass) was experimentally highlighted by growing the strength values. The best performing values of the compressive strength were reached under the conditions of replacing the cement with glass powder of 36 wt. % (variant 4), i.e. 42.6 MPa after 7 days, 47.1 MPa after 28 days, and 49.8 MPa after 56 days. The values reached in this experiment are comparable to those reported in the paper [2] after similar durations of the curing process, with the remark that the durations of the process were much longer (up to 90 days) and, at the same time, the maximum percentage of glass powder was only 25 %. A similar influence on the improvement of flexural strength was found depending on the duration of curing process, The highest values of this type of strength were obtained after 56 days of curing (variant 4) being reached 7.8-11.4 MPa.

The modulus of elasticity tended to decrease slightly, its value dropping from 30.1 to 25.2 GPa, while water uptake values remained almost constant within a narrow range (3.3-3.6 vol. %).

The investigation of the microstructural features of the four concrete specimens (Figure 2) provided typical images of concretes in which the proportion of added pozzolanic glass as a cement substitute was in a pronounced increase.

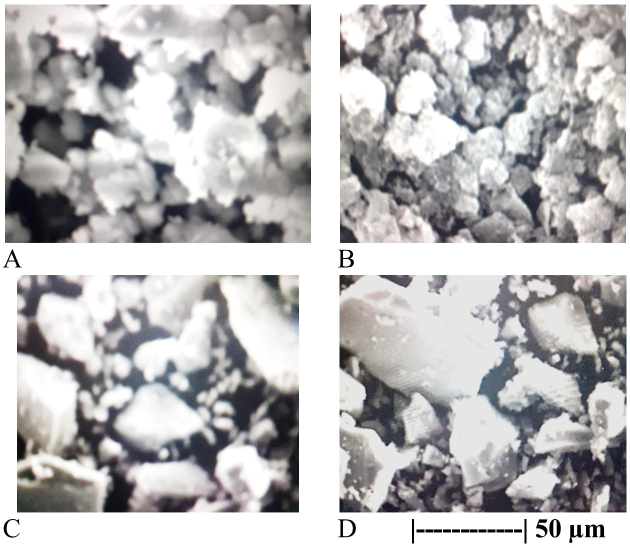

Figure 2. Images of microstructural peculiarities of experimental concrete samples
A – variant 1; B – variant 2; C – variant 3; D – variant 4.

3.2 Discussion

Given that the industrial manufacture of Portland cement, which for over 100 years has represented the main binder in the producing process of construction concrete, has become a real problem for the entire planet due to its decisive contribution to CO_2 emissions into the atmosphere with negative consequences in the future, its elimination or partial use by using other technical and material options constitutes one of the main current concerns of researchers in the world.

Important steps are already known towards testing several methods of cement substitution by adopting waste or natural alumina-silicate products activated in highly alkaline aqueous solutions [32, 33].

The current work refers to recently discovered ability of recycled commercial glass (soda-lime glass type) to be transformed by fine grinding from an inert glassy material into a pozzolanic glass with very similar properties to those of Portland cement.

The characteristics of the experimental concrete prepared by authors through partially substituting up to 36 % of the common cement with coloured pozzolanic glass (amber) showed the viability of the adopted procedure and achieving compressive and flexural strengths both after only 7 days (early time) and at the end of the usual curing process (28 and 56 days).

4. CONCLUSIONS

The current work aimed at obtaining a high-performance concrete under conditions of significant reduction of cement consumption by replacing up to 36 % of it with pozzolanic commercial glass (soda-lime glass type) obtained by finely grinding recycled glass waste. Experimental results showed the possibility to obtain high compressive and flexural strengths after a maximum of 56 curing days (49.8 and 11.4 MPa, respectively). In this experiment, amber glass waste was used for the first time and the superplasticizer adopted to reduce water consumption was a wood-based material (sodium lignosulfonate).

5. REFERENCES

1. Kalakada, Z., Doh, J., Zi, G., Utilization of coarse glass powder as pozzolanic cement-A mix design investigation, *Construction and Building Materials*, Elsevier, Vol. 240, (2020). https://doi.org/10.1016/j.conbuildmat.2019.117916
2. Poudel, S., Bhetuwal, U., Kharel, P., Khatiwada, S., Diwakar, K.C., Dhital, S., Lamichhane, B., Yadav, S.K., Suman, S., Waste glass as a partial

cement replacement in sustainable concrete: Mechanical and fresh properties review, *Buildings,* MDPI, Senouci, A., Maherzi, W. (acad. eds.), Vol. 15, No. 6, (2025). https://doi.org/10.3390/buildings15060857

3. Okeke, K.L., Adedeji, A.A., A review on the properties of concrete incorporated with waste glass as a substitute for cement, *Epistemics in Science, Engineering and Technology,* Webs Journals, Vol. 5, No. 1, pp. 389-400, ISSN: 2384-6844, (2015).
4. Taha, B., Nounu, G., Properties of concrete contains mixed colour waste recycled glass as sand and cement replacement, *Construction and Building Materials,* Elsevier, Vol. 22, pp. 713-720, (2008). https://doi.org/10.1016/j.conbuildmat.2007.01.09
5. Nodehi, M., Ren, J., Shi, X., Debbarma, S., Ozbakkaloglu, T., Experimental evaluation of alkali-activated and Portland cement-based mortars prepared using waste glass powder in replacement of fly ash, *Construction and Building Materials,* Elsevier, Vol. 394, (2021). https://doi.org/10.1016/j,conbuildmat.2023.132124
6. Tucker, E.L., Ferraro, C.C., Laux, S.J., Townsend, T.G., Economic and life cycle assessment of recycling municipal glass as a pozzolan in Portland cement concrete production, *Resources, Conservation and Recycling,* Elsevier, Vol. 129, pp. 240-247, (2018), https://doi.org/10.1016/j.resconrec.2017.10.025
7. Mc Carthy, M.J., Dyer, T.D., Pozzolanas and pozzolanic materials, in *Lea'chemistry of cement and concrete,* Hewlett, P.C. (ed.), Elsevier, Butterworth-Heinemann, Oxford, UK, Chapter 10, pp. 471-632, ISBN: 978-0-08-100773-0, (1998).
8. Burhan, L., Ghafor, K., Mohammed, A., Modeling the effect of silica fume on the compression, tensile strength and durability of NSC and HSC in various strength ranges, *Journal of Building Pathology and Rehabilitation,* Springer Nature Switzerland, Vol. 4, No. 1, (2019). https://doi.org/10.1007/s41024-019-0058-4
9. Hamada, H.M., Abed, F., Katman, H.Y.B., Humada, A.M., Al Jawahery, M.S., Majdi, A., Yousif, S.T., Thomas, B.S., Effect of silica fume on the properties of sustainable cement concrete, *Journal of Materials Research and Technology*, Elsevier, Vol. 24, pp. 8887-8908, (2023). https://10.1016/j.jmrt.2023.05.147
10. Guo, P., Meng, W., Nasiff, H., Gou, H., Bao, Y., New perspectives on recycling waste glass in manufacturing concrete for sustainable civil infrastructure, *Construction and Building Materials,* Elsevier, Vol. 257, (2020). https://doi.org/10.1016/j.conbuildmat.2020.119579
11. Mohajerani, A., Vajna, J., Cheung, T.H.H., Kurmus, H., Arulrajah, A., Horpibulsuk, S., Practical recycling applications of crushed waste glass in construction materials: A review, *Construction and Building Materials*, Elsevier, pp. 443-467, (2017). https://doi.org/10.1016/j.conbuildmat.2017.09.005
12. Berdnyk, O., Vyhovskyi, S., Use of waste glass in concrete: A review, *Construction, Architecture, Transfer of Innovative Technologies,* Vol. 6, No. 1, pp. 33-39, (2023). https://doi.org/10.32347/tit.2023.61.0105
13. Li, Q., Qiao, H., Li, A., Li, G., Performance of waste glass powder as a pozzolanic material in blended cement mortar, *Construction and Building Materials,* Elsevier, Vol. 324, (2022). https://doi.org/10.1016/j.conbuildmat.2022.126531
14. Mahajan, L.S., Bhagat, S.R., Utilization of pozzolanic material and waste glass powder in concrete, in *Recent trends in construction technology and management,* Part of the book series: Lecture Notes in Civil Engineering, Vol. 260, Springer Link, Ranadive, M.S., Bibhuti, B., Yusuf, A.M. (eds.), pp. 201-206, (2022). https://link.springer.com/chapter/10.1007/978-981-19-2145-2_16
15. Rani, G.Y., Krishna, T.J., Murali, K., Strength studies on effect of glass waste in concrete, *Materials Today: Proceedings*, Elsevier, Vol. 46, Part 17, pp. 8817-8821, (2021). https://doi.org/10.1016/j.matpr2023.04.328
16. Manzoor, A., Kumar, E.Y., Sharma, L., Comparison of partially replaced concrete by waste glass with control concrete, *Materials Today: Proceedings*, Elsevier, Vol. 68, Part 4, pp. 1129-1134, (2022). https://doi.org/10.1016/j.matpr2022.09.092
17. Siddika, A., Hajimohammadi, A., Ferdous, W., Sahajwalla, V., Roles of waste glass and the effect of process parameters on the properties of sustainable cement and geopolymer concrete-A state-of-the-art review, *Polymers,* MDPI, Blanco, I., Catauro, M. (acad. eds.), Vol. 13, No. 22, (2021). https://doi.org/10.3390/polym13223935

18. He, Z., Zhan, P., Du, S., Liu, B., Yuan, W., Creep behavior of concrete containing glass powder, *Composites Part B Engineering*, Elsevier, Vol. 166, pp. 13-20, (2019). https://doi.org/10.1016/j.compositesb.2018.11.133
19. Schwartz, N., Cam, H., Neithalath, N., Influence of a fine glass powder on the durability characteristics of concrete and its comparison to fly ash, *Cement and Concrete Composites,* Elsevier, Vol. 30, No. 6, pp. 486-496, (2008). https://doi.org/10.1016/j.cemconcomp.2008.02.001
20. Omran, A., Harbec, D., Tagnit-Hamou, A., Gagne, R., Production of roller-compacted concrete using glass powder: Field study, *Combustion and Building Materials,* Elsevier, Vol. 133, pp. 450-458, (2017). https://doi.org/10.1016/j.conbuildmat.2016.12.099
21. Shayan, A., Xu, A., Performance of glass powder as a pozzolanic material in concrete: A field trial on concrete slabs, *Cement and Concrete Research,* Elsevier, Vol. 36, No. 3, pp. 457-468, (2006). https://doi.org/10.1016/j.cemconres.2005.12.021
22. Du, H., Tan, K.H., Properties of high volume glass powder concrete, *Cement and Concrete Composites,* Elsevier, Vol. 75, pp. 22-29, (2017). https://doi.org/10.1016/j.cemconcomp.2016.10.010
23. Wang, H.Y., Zeng, H-H., Wu, J-Y., A study on the macro and micro properties of concrete with LCD glass, *Construction and Building Materials*, Elsevier, Vol. 50, pp. 664-670, (2014). https://doi.org/10.1016/j.conbuildmat.2013.09.015
24. Ez-zaki, H., El Gharbi, B., Diouri, A., Development of eco-friendly mortars incorporating gall and shell powders, *Construction and Building Materials*, Elsevier, Vol. 159, pp. 198-204, (2018). https://doi.org/10.1016/j.conbuildmat.2017.10.125
25. Islam, G.M.S., Rahman, M.H., Kazi, N., Waste glass powder as partial replacement of cement for sustainable concrete practice, *International Journal of Sustainable Built Environment*, Elsevier, Vol. 6, No. 1, pp. 37-44, (2017). https://doi.org/10.1016/j.ijsbe.2016.10.005
26. Tahwia, A.M., Heniegal, A.M., Abdellatief, M., Tayeh, B.A., Elrahman, M.A., Properties of ultra-high performance geopolymer concrete incorporating recycled waste glass, *Case Studies in Construction Materials*, Elsevier, Vol. 17, (2022). https://doi.org/10.1016/j.cscm.2022.e01393
27. Paunescu, L., Volceanov, E., Dragoescu, M.F., Paunescu, B.V., Fly ash-geopolymer composite obtained by addition of recycled post-consumer packaging bottle, *Nonconventional Technologies Review*, ”Politehnica” Publishing House, Timisoara, Romania, Vol. 28, No. 4, pp. 16-21, (2024). https://www.revtn.ro/index.php/revtn/article/view/487/435
28. Li, G., Shao, Y., Fang, Y., Li, W., Lin, Y., Yan, D., Effect of waste glass on slurry rheological properties of cement and concrete, *Journal of Physics: Conference Series,* IOP Publishing Ltd., Vol. 2044, (2021). https://doi.org/10.1088/1742-6596/2044/1/012015
29. Gupta, J., Jethoo, A., Lata, N., Assessment of mechanical properties by using powder waste glass with cement in concrete mix, *Proceedings of the IOP Conference Series: Materials Science and Engineering,* Tamil Nadu, India, April 9-10, IOP Publishing Ltd., Bristol, UK, Vol. 872, (2020). https://doi.org/10.1088/1757-899X/872/1/012122
30. Abdias, M.W.M., Blanche, M.M., Nana, U.J.P., Abanda, H.F., François, N., Chrispin, P., River sand characterization for its use in concrete: A revue, *Open Journal of Civil Engineering,* Scientific Research publisher, Vol. 13, No. 2, (2023). https://doi.org/10.4236/0jce.2023.132027
31. Patel, H., *Coarse aggregate: Types and their role in construction*, Brick & Bolt Home Construction Company, Pluckwalk Technologies Pvt. Ltd., Bangalore, India, (2024). https://www.bricknbolt.com/
32. Davidovits, J., Geopolymers: Inorganic polymeric new materials, *Journal of Thermal Analysis Calorimetry*, Geopolymer Institute, Saint Quentin, France, Vol. 37, No. 8, pp. 1633-1656, (1991). https://www.geopolymer.org/wp-content/uploads/J_THERMAL.pdf
33. Davidovits, J., Davidovits, M., Davidovits, N., *Process for obtaining a geopolymeric alumino-silicate and products thus obtained,* US Patent, No. 5342595, (1992).