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Utilisation of Silicate-Containing Waste in the Production of High-Density Concrete

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The recycling of glass waste is an increasingly important challenge, as glass constitutes a valuable secondary raw material. The volume of discarded glass accumulating in the environment is approaching the scale of natural geological resources consumed by industry. Environmentally, glass is difficult to degrade due to its exceptional chemical durability—it is resistant to water, frost, organic and mineral acids, salts, and microbial activity. This study investigates the use of glass waste as a partial replacement for fine aggregate in heavyweight concrete production, offering a sustainable solution to both construction material demand and municipal waste management. Special emphasis is placed on the effect of silicate-containing waste on the physical and mechanical performance of concrete. Experimental results confirm the feasibility of incorporating crushed glass cullet (1.25–0.05 mm) into concrete mixtures. The influence of different particle size fractions on compressive strength is analyzed, demonstrating the potential of glass waste to enhance concrete properties while supporting circular economy practices. The best strength properties were achieved with optimal glass frit proportions: the use of fine fraction (less than 0.9 mm) and coarse fraction (1.25–2.5 mm) resulted in a significant increase in strength (17–20 %) compared to the control composition.

1. Introduction

The global construction industry is undergoing fundamental changes driven by the urgent need to reduce environmental impact while maintaining structural performance and economic viability. With the constant depletion of natural aggregates such as sand and gravel and the growing problem of solid waste accumulation, using recycled materials in concrete production is no longer a niche innovation — it is an environmental necessity. Among the various waste streams generated by industrial and consumer activities, glass waste (cullet) represents a significant and underutilised resource. Every year, millions of t of glass are discarded worldwide, resulting in landfills due to inefficient recycling systems and contamination issues. However, glass waste has several physical and chemical properties that make it an auspicious material for reuse in construction. Consisting mainly of amorphous silica (SiO_2), as well as sodium, calcium and minor oxides, glass waste is chemically stable, non-porous and highly resistant to biological degradation and chemical attack. Recent advances in materials science have shown that waste glass can be effectively used as a partial replacement for fine and coarse aggregates or even as an additional binding material when finely ground. The use of glass cullet not only increases the environmental friendliness of concrete but can also improve some performance parameters, such as durability, thermal stability and impermeability.
However, different sources recommend different percentages of glass waste additives, depending on the additive type used. Thus, in a study on the use of glass waste microparticles to produce self-compacting concrete mixtures, it was found that the optimal percentage of glass waste for self-compacting concrete is 5 % as a partial replacement for cement, which increases strength by more than 18 % compared to the control mixture (Sharifi et al., 2016). The work of Martina et al (2022) work on using glass powder waste as a partial

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replacement for cement in concrete production showed that the optimal waste additive content is 4 %, which increases strength at the design age by 5 %.
A review of the effect of recycled glass waste on the properties of high-strength concrete shows that the most optimal use is crushed glass waste as a replacement for fine aggregate, with a waste content of 20 to 30 % (Hamada et al., 2016).
Research into the effect of glass powder particle size is of particular interest when using glass powder. For example, there are individual studies showing a possible increase in strength with a decrease in particle size. A number of authors note that as the size and angularity of glass powder particles increase, their mechanical and rheological properties deteriorate and the risk of injury increases (Xiao et al., 2023). There are no comprehensive studies containing solutions for the complete recycling of glass cullet of different fractions.
Every year, Kazakhstan generates about 4.5-5 million t of solid domestic waste, of which 6-17 % is glass waste in various regions. However, only 15 % of the total amount of waste is recycled. Recycling glass waste is a pressing issue, as glass is a valuable secondary resource.
At present, glass is not recycled in its entirety for several reasons: the heterogeneity of the chemical composition of the raw materials, the presence of contaminants, the high cost of separating glass from mixed municipal waste, and the impossibility of oxidising or decomposing glass. Most of the broken glass consists of container and sheet glass, which, in terms of chemical composition, belongs to sodium-calcium-silicate glass.
In recent years, research aimed at developing specific technical solutions for industrial enterprises on the use of waste has been gaining increasing interest in Kazakhstan (Sadenova et al., 2024).
This study is devoted to investigating the possibility of using glass waste with particle sizes ranging from 1.25 mm to 0.05 mm as a partial replacement for aggregate in the production of heavy concrete. The results of this study aim to bridge the gap between waste management and sustainable construction by offering optimal solutions to reduce dependence on landfills, consumption of natural aggregates and greenhouse gas emissions associated with traditional concrete production.

2. Materials and Experimental Design

This study aimed to investigate heavyweight concrete in which part of the fine aggregate (natural sand) was replaced by crushed glass waste (glass cullet). Experimental work was carried out at the Center for Competence and Technology Transfer of D. Serikbayev East Kazakhstan Technical University.
The reference concrete mixture was composed of the following components: CEM I 42.5H Portland cement as the binder; crushed stone with a grain size of 5–10 mm as the coarse aggregate; natural sand with a fineness modulus of 2.49 as the fine aggregate; and a plasticising admixture to enhance workability. Potable water was used for all mixtures. In the modified compositions, a portion of the sand was substituted by glass cullet. The glass waste was pre-crushed to the desired particle size: a jaw crusher was used to obtain coarse fractions, while a dual-chamber vibratory mill (batch-type) was employed to produce finer particles.
In laboratory conditions, specimen preparation followed a standardised protocol. Cement, crushed stone, sand, and the glass component were first dry-mixed to ensure uniform distribution. Water was blended with the plasticiser and then added to the dry mix. The entire batch was thoroughly mixed until a homogeneous consistency was achieved. The resulting concrete was cast into cubic moulds measuring 100 × 100 × 100 mm. A batch of six cube samples was produced for each composition. After 24 h, the specimens were demoulded and transferred to a KNT-120 curing chamber, where they were stored at a constant temperature of 20 ± 2 °C and a relative humidity of 95 % for a period of 28 d. Upon curing completion, mechanical testing was conducted using a P-125 hydraulic testing press equipped with two measurement ranges: 0–625 kN and 0–1250 kN, by GOST 10180-2012.
Two experimental series were carried out based on the granulometric characteristics of the glass waste:
1) The first series involved a coarse glass cullet, composed of approximately 80 % particles in the 1.25–5 mm range.
2) The second series utilised fine glass waste with particles smaller than 0.9 mm.
To determine the influence of glass content on the concrete's physical and mechanical properties, initial trials were conducted with varying replacement levels of sand: 0 %, 5 %, 10 %, 15 %, 20 %, and 25 %. The coarse fraction consists of approximately 80 % particles with a size of 1.25–5 mm, while the fine fraction consists of fine glass waste with a particle size of less than 0.9 mm. The optimal content for coarse and fine glass fractions was selected separately based on the results to achieve maximum strength. Subsequent batches were prepared using these optimal replacement levels, further differentiated by particle size distribution. For coarse glass cullet, the following size fractions were used: 1.25–2.5 mm, 0.2–1.25 mm, and 0.08–0.2 mm. Two fractions were applied for fine cullet: 0.14–0.9 mm and particles smaller than 0.14 mm.
The overall experimental design is illustrated in Figure 1, providing a schematic overview of the material composition and test procedure.

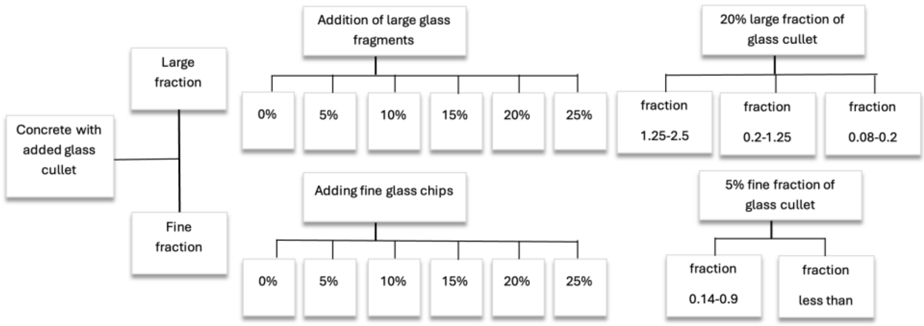

Figure 1: Experimental research design

3. Results and discussion

The strength and strength variation of samples with different contents of coarse glass waste (0 %, 5 %, 10 %, 15 %, 20 % and 25 %) are presented in Table 1. These results serve as a basis for selecting the optimal percentage content of coarse glass waste in concrete.

Table 1: Test results for samples with large glass waste

Glass content, %	Strength at the age of 28 d, MPa	Strength increase, MPa	Strength increase, %
0	35.3	0.0	0.0
5	37.1	1.8	5.1
10	38.0	2.7	7.7
15	39.0	3.7	10.6
20	39.4	4.1	11.7
25	37.7	2.4	6.9

Table 1 shows the compressive strength values of samples without glass components and with glass content in concrete of 5 %, 10 %, 15 %, 20 % and 25 %. Table 1 also shows the calculated values of the increase in strength of the samples and their percentage ratio. Table 1 shows that all samples containing glass cullet exhibit an increase in strength compared to the base composition sample without glass component. For visual analysis of changes in strength dynamics, a histogram of strength is plotted in Figure 2a, and a histogram of strength change in absolute and percentage terms is plotted in Figure 2b.

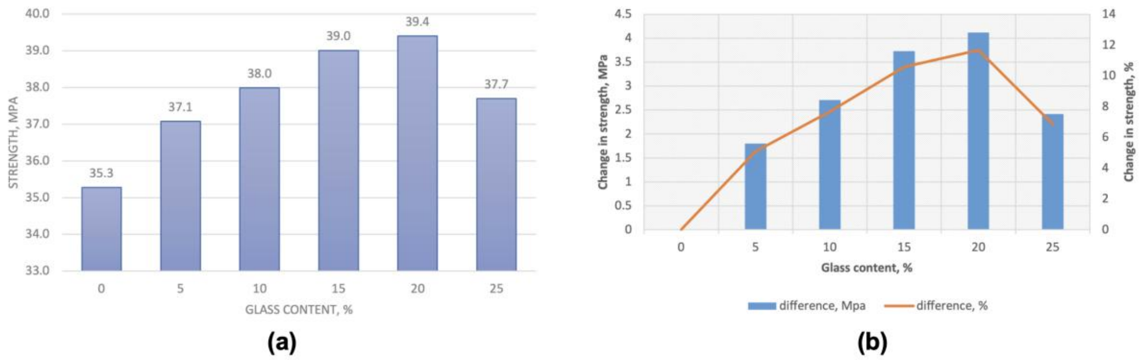

Figure 2: (a) Strength depending on the amount of glass cullet; (b) Change in strength depending on the amount of glass cullet

Analysis of the results showed that the increase in strength ranged from 1.8 to 4.1 MPa, which amounted to 5.1 to 11.7 % in percentage terms. The maximum increase in strength was observed at a 20 % glass cullet content. The strength increased by 11.7 %, which amounted to 4.1 MPa. Table 1 also shows that when glass cullet is added from 5 to 25 %, the strength increases from 35.5 to 39.4 MPa. When 25 % silicate-containing waste is

added, the strength decreases compared to samples containing 20 % glass cullet, but the strength remains 2.4 MPa (6.9 %) higher than the sample without glass waste.
The experiment continued by producing specimens by separating glass waste fractions at the selected optimal percentage content of silicate-containing waste of 20 %.
Table 2 presents the results of testing samples with 20 % glass cullet, particle sizes ranging from 1.25 to 2.5 mm, 0.2 to 1.25 mm, 0.08 to 0.2 mm, and without waste.

Table 2: Test results for samples with 20 % coarse glass cullet

Glass particle sizes	Strength at the age of 28 d, MPa	Strength increase, MPa	Strength increase, %
without glass	35.3	0.0	0.0
fraction 1.25-2.5	41.3	6.0	17.1
fraction 0.2-1.25	39.2	3.9	11.1
fraction 0.08-0.2	35.9	0.6	1.8

Table 2 shows the compressive strength values and the calculated values of the increase in strength of the samples and their percentage ratio. Table 2 shows that all samples containing glass cullet exhibit an increase in strength compared to those without a glass component. For visual analysis of changes in strength dynamics, a strength histogram is plotted in Figure 3a, and a histogram of strength changes in absolute and percentage terms is plotted in Figure 3b. Analysis of the results showed that the increase in strength ranged from 0.6 to 6.0 MPa, which amounted to 1.8 to 17.1 % in percentage terms. The maximum increase in strength was observed at a 20 % content of silicate-containing waste with a fraction of 1.25 to 2.5 mm. The increase in strength was 17.1 %, which amounted to 6.0 MPa. Furthermore, Table 2 shows that when 20 % of glass cullet with particle sizes ranging from 0.2 to 1.25 mm is added, the strength decreases to 39.2 MPa, but the strength remains 3.9 MPa (11.1 %) higher than that of the base sample without glass cullet.

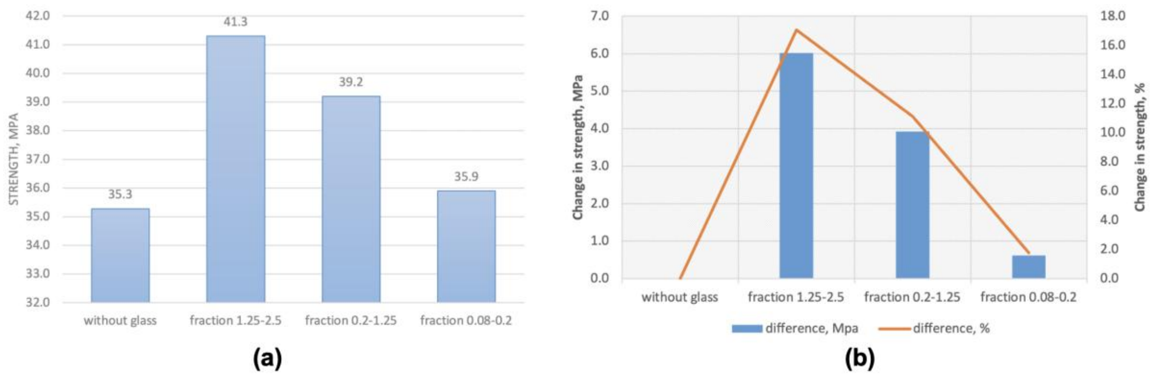

Figure 3: (a) Strength depending on the grain composition of cullet; (b) Change in strength depending on the grain composition of cullet

Table 3 presents samples' strength and strength variation with different contents of fine glass waste (0 %, 5 %, 10 %, 15 %, 20 %, and 25 %). These results are used to select the best percentage content of coarse glass cullet in concrete.

Table 3: Results of testing samples with fine glass waste

Glass content, %	Strength at the age of 28 d, MPa	Strength increase, MPa	Strength increase, %
0	32.8	0.0	0.0
5	39.4	6.6	20.1
10	35.1	2.3	7.0
15	33.9	1.1	3.4
20	27.8	-5.0	-15.2
25	26.3	-6.5	-19.8

Table 3 shows the compressive strength values of samples without glass components and with glass content in concrete of 5 %, 10 %, 15 %, 20 % and 25 %. The table also shows the calculated values of the change in strength of the samples and their percentage ratio. Table 3 shows that for some of the samples containing glass cullet, there is an increase in strength, while for some of the samples, there is a decrease in strength compared to the strength of the sample without a glass component. For visual analysis of changes in strength dynamics, a histogram of strength is plotted in Figure 4a, and a histogram of strength change in absolute and percentage terms is plotted in Figure 4b. The results showed that when glass waste was added from 5 to 15 %, the strength increased from 1.1 to 6.6 MPa compared to samples without glass, which amounted to 3.4 to 20.1 % in percentage terms. The maximum increase in strength is observed at a 5 % glass waste content. The increase in strength was 20.1 %, which amounted to 6.6 MPa. Table 3 also shows that when the glass waste content is between 5 and 15 %, the strength increases from 32.8 to 39.4 MPa. When 20 and 25 % of silicate-containing waste are added, the strength decreases by 5.0 MPa (15.2 %) and 6.5 MPa (19.8 %), respectively, compared to samples without glass cullet.

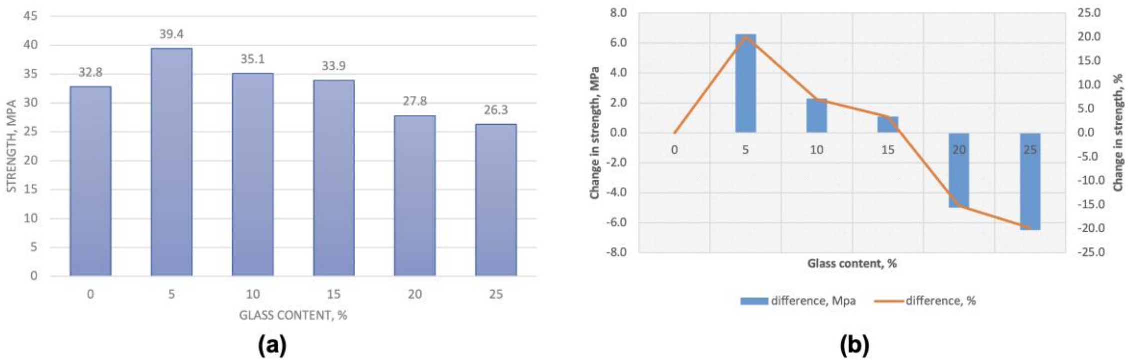

Figure 4: (a) Strength depending on the grain composition of cullet; (b) Change in strength depending on the grain composition of cullet.

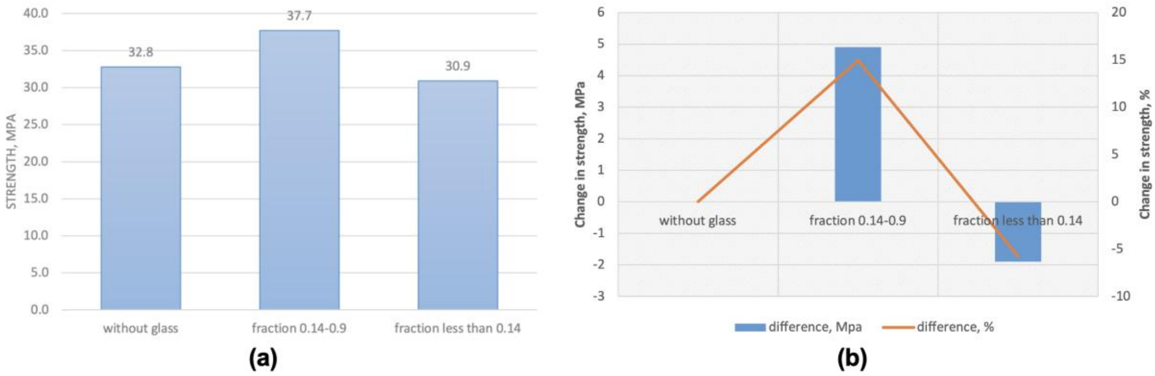

Figure 5: (a) Strength depending on the grain composition of cullet; (b) Change in strength depending on the grain composition of cullet

The experiment continued with the production of samples with the separation of glass waste fractions at a selected percentage content of silicate-containing waste of 5 %.

Table 4 presents the results of testing samples with 5 % cullet, particle sizes ranging from 0.14 to 0.9 mm, less than 0.14 mm, and without waste.

Table 4: Test results for samples with 5 % fine glass cullet

Glass particle sizes	Strength at the age of 28 d, MPa	Strength increase, MPa	Strength increase, %
without glass	32.8	0	0
fraction 0.14 - 0.9	37.7	4.9	14.9
fraction less than 0.14	30.9	-1.9	-5.8

Table 4 shows the compressive strength values, calculated values of strength change in samples with fine glass waste, and their percentage ratio. Table 4 shows that samples containing 5 % glass cullet particles ranging from 0.14 to 0.9 mm exhibit increased strength compared to samples without glass components, while samples containing particles smaller than 0.14 mm exhibit decreased strength. For visual analysis of changes in strength dynamics, a strength histogram is plotted in Figure 5a, and a histogram of strength changes in absolute and percentage terms is plotted in Figure 5b. Analysis of the results showed that for samples with silicate-containing waste particles ranging from 0.14 to 0.9 mm, the strength increased by 4.9 MPa, which amounted to 14.9 %. For samples with silicate-containing waste particles smaller than 0.14 mm, the strength decreased by 1.9 MPa, which amounted to 5.8 %.

The research confirmed the possibility of improving the strength characteristics of heavy concrete by partially replacing traditional aggregate with glass waste of various sizes. The most significant increase in strength was recorded when 20 % of the glass cullet with a fraction of 1.25–2.5 mm was added (by 17.1 %). When the glass frit content was increased to 25 %, a decrease in strength was observed, which is probably due to a violation of the optimal grain composition, leading to an increase in porosity and deterioration of the binder distribution, which reduces strength. For the fine fraction, the most significant increase in strength was observed when 5 % of fine glass cullet (less than 0.9 mm) was added (by 20.1 %). And remove the blue text as the previous sentence has been rephrased and when 5 % of the fine glass cullet (less than 0.9 mm) was added (by 20.1 %). However, an excessive content of glass cullet, especially the finely dispersed fraction, leads to a decrease in strength compared to the base values. This may be due to an excessive increase in specific surface area and water absorption, which has a negative effect on the formation of cement stone. These results emphasize the need to carefully select the optimal content and particle size distribution of glass cullet to achieve the maximum strengthening effect in concrete. Thus, the optimal content and grain composition of glass waste play a key role in improving the mechanical properties of concrete mixes and can be used to develop effective and environmentally friendly building materials and create sustainable ecological construction.

4. Conclusions

The study's results confirm the feasibility of using a glass cullet as a partial replacement for fine aggregate in the production of heavy concrete. It has been established that the introduction of silicate-containing waste improves the strength characteristics of concrete mixes, with the additive's effectiveness depending on both its percentage content and particle size. The greatest increase in strength was observed when adding 20 % glass cullet fraction 1.25–2.5 mm — strength increased by 17.1 %: 5 % glass cullet less than 0.9 mm in size — strength increased by 20.1 %. When the glass cullet content exceeds the above values, a decrease in strength is observed, especially when using particles smaller than 0.14 mm due to the increased specific surface area and possible disruption of the cement stone structure. Thus, the optimal use of recycled glass improves the physical and mechanical properties of concrete, contributes to solving environmental problems associated with the disposal of glass waste, and reduces the consumption of natural resources. The data obtained can be used to develop environmentally sustainable building materials for a new generation. Further development of technical solutions for construction companies on the rational and waste-free use of cullet, the development of recipes for the optimal content of the mixture of fractions, and the use of individual fractions to solve specific problems is of further interest.

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