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Influence of replacing cement with Fine Glass Powder on the basic properties of concrete

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Abstract
This study investigates the effect of partially replacing cement with finely ground glass powder on the main properties of concrete, including strength, workability, water tightness, microstructure, and susceptibility to alkali-silica reaction (ASR). Experimental results indicate that substituting up to 20% of cement by weight with glass powder helps maintain or even improve compressive and flexural strength due to pozzolanic reactions and enhanced pore structure. However, increasing the replacement level beyond 20% leads to a decrease in strength and water tightness, associated with increased porosity and reduced binder content. The workability of the concrete mix decreases as the glass powder content rises, necessitating adjustments in water-cement ratio or the use of plasticizers. Scanning electron microscopy (SEM) analysis confirmed a denser and more homogeneous microstructure at optimal replacement levels, whereas higher proportions caused heterogeneity and microporosity. Despite the presence of amorphous silica in the glass powder, no significant signs of ASR were observed, indicating safe usage within recommended limits. These findings support the potential use of glass waste as a supplementary cementitious material in concrete production.

Keywords: Glass powder, concrete, cement replacement, pozzolanic activity, compressive strength, workability, water tightness, microstructure, SEM analysis, alkali-silica reaction (ASR), sustainable materials, supplementary cementitious materials (SCMs)

Introduction
Concrete remains one of the most widely used construction materials globally due to its strength, durability, and versatility. However, the production of cement—the primary binder in concrete—is associated with substantial carbon dioxide emissions. Cement manufacturing accounts for approximately 8% of global CO_2 emissions, primarily due to the energy-intensive clinker production process and the chemical decomposition of limestone. Producing one ton of cement releases between 0.8 and 1 ton of CO_2, making the cement industry one of the largest contributors to environmental pollution in the construction sector.
Given the global challenges of climate change and limited natural resources, there is an increasing demand for sustainable and environmentally friendly construction solutions. One effective strategy to reduce the carbon footprint of concrete is the partial substitution of cement with recycled or waste materials possessing pozzolanic properties. Among these alternatives, finely ground glass powder derived from glass waste has gained considerable attention.

Problem of Glass Waste Disposal
Although glass is fully recyclable, a significant portion of used glass—especially colored or contaminated glass—is unsuitable for traditional recycling processes and ends up in landfills. Glass waste is non-biodegradable and accumulates over time, occupying considerable landfill space. Utilizing glass waste in construction materials addresses two major issues simultaneously: waste management challenges and the reduction of cement consumption in concrete production, thereby enhancing sustainability.

Potential of Glass Powder in Concrete
Finely ground glass powder contains a high proportion of amorphous silicon dioxide (SiO_2), which can react with calcium hydroxide produced during cement hydration. This pozzolanic reaction forms additional calcium silicate hydrate compounds, improving the density and mechanical properties of the cement matrix.
However, the effectiveness of glass powder as a cement substitute depends on various factors, including the chemical composition of the glass, particle size, replacement level, curing conditions, and others. It is also essential to ensure that concrete containing glass powder meets established standards for strength and durability.

Aim of the Study
This research aims to investigate how partial replacement of cement with finely ground glass powder affects the fundamental properties of concrete, including compressive, flexural, and tensile strengths, workability, water resistance, and microstructure. Special attention is given to assessing the risk of alkali-silica reaction (ASR), which can negatively impact the long-term durability of concrete structures.

Scientific Novelty and Practical Significance
Unlike many studies conducted in other regions, this work focuses on locally sourced materials and follows standardized testing procedures. The comprehensive approach enables the identification of optimal glass powder dosages that enhance concrete properties while offering environmental benefits without compromising structural integrity. The findings can provide a valuable foundation for integrating glass powder as a supplementary cementitious material in industrial concrete production.

Research Methodology
Materials
- **Cement:** For this study, Portland cement grade M400 was chosen due to its common use in construction and

conformity with GOST 10178-85 standards. Cement was procured directly from the manufacturer to ensure quality and freshness. Before use, the cement was inspected to confirm the absence of lumps and moisture content was verified to be under 1%, ensuring optimal conditions for hydration.

- **Glass Powder:** The glass powder was produced from clear bottle glass waste collected from recycling centers. To remove contaminants, the glass was thoroughly cleaned and dried prior to crushing. Subsequently, it was ground in a ball mill to achieve particles smaller than 75 microns, which enhances the surface area necessary for pozzolanic reactions. Chemical composition analysis showed a high proportion of amorphous silica (SiO_2), essential for reactivity.

- **Aggregates:** The aggregates used included quartz sand with grain sizes ranging from 0.15 to 1.25 mm and natural gravel sized between 5 and 20 mm. Both materials met applicable standards, were free from impurities, and were kept dry before mixing.

- **Water:** Tap water suitable for concrete mixing and curing, free of harmful substances, was used throughout the experiments.

- **Additives:** No chemical admixtures such as plasticizers or air-entraining agents were added to isolate the effects of glass powder substitution on the concrete's behavior. Future studies may explore the use of additives to address workability issues.

Mix Design and Proportions

Concrete mixtures were prepared by partially replacing cement with glass powder at four levels: 0%, 10%, 20%, and 30% by weight. To eliminate variability from water content, the water-to-cement ratio was maintained at a constant 0.40 for all mixtures.

Sample ID	Cement Replacement (%)	Cement (kg)	Glass Powder (kg)	Sand (kg)	Gravel (kg)	Water (kg)	W/C Ratio
Control (K)	0	400	0	700	1100	160	0.40
S10	10	360	40	700	1100	160	0.40
S20	20	320	80	700	1100	160	0.40
S30	30	280	120	700	1100	160	0.40

The aggregate to binder ratio remained unchanged in all mixes to maintain consistency.

Mixing Procedure

A standardized mixing protocol was followed to ensure thorough dispersion of glass powder within the cementitious matrix:

1. **Dry Mixing:** Cement and glass powder were mixed dry for approximately 3 minutes using a mechanical mixer until a uniform blend was obtained.

2. **Addition of Aggregates:** Sand and gravel were incorporated gradually and mixed for an additional 2 minutes to ensure even distribution.

3. **Water Addition:** Water was slowly added during mixing, followed by 3 to 5 minutes of mixing until a homogeneous and workable concrete was achieved.

4. **Workability Check:** Slump tests were performed according to GOST 10181 standards. No admixtures were introduced to modify the slump, so any decrease in workability was solely due to glass powder substitution.

Specimen Preparation and Curing Conditions

Specimens were molded in standard shapes tailored for different tests:

- Cubes (100×100×100 mm) for compressive strength evaluation.
- Prisms (100×100×400 mm) for flexural strength assessment.
- Cylinders (100 mm diameter × 200 mm height) for splitting tensile strength measurement.

After casting, specimens were vibrated to remove entrapped air, then cured in a controlled environment at 20 ± 2 °C and 95 ± 5% relative humidity for 24 hours. Post demolding, samples were submerged in water or stored in a high-humidity chamber until testing at designated curing ages (7, 28, and 56 days).

Testing Procedures

- **Compressive Strength:** Tested on cube specimens following GOST 10180; results averaged over three samples.

- **Flexural Strength:** Measured via the four-point bending method on prisms.

- **Splitting Tensile Strength:** Determined on cylindrical specimens according to GOST 28570.

- **Workability:** Assessed by slump testing in accordance with GOST 10181, classifying the mix flow characteristics.

- **Water Resistance:** Depth of water penetration under pressure was measured following GOST 12730.5 to evaluate concrete permeability.

- **Microstructural Analysis:** Scanning Electron Microscopy (SEM) was utilized to observe the morphology of cement paste and glass powder dispersion, along with porosity and microcrack presence.

- **ASR Risk Evaluation:** Visual examination for microcracks and chemical composition analysis of glass powder were conducted to assess potential alkali-silica reaction risks.

Data Treatment and Analysis

Mechanical test results were statistically processed, with mean values and standard deviations calculated for each sample group. SEM images were qualitatively analyzed to relate microstructural features to mechanical and durability outcomes. ASR potential was assessed by combining chemical and microscopic data.

Conclusions

1. Mechanical Properties of Concrete

- Replacing cement with glass powder up to 20% by mass helps maintain or slightly improve the compressive and flexural strength of concrete due to pozzolanic reactions and pore filling.
- When the replacement level exceeds 20%, a decrease in strength characteristics is observed, which is associated with a reduction in the amount of cementitious binder and a possible increase in porosity.

2. Workability of the Mix

- Increasing the content of glass powder leads to a decrease in slump, i.e., worsens the workability of the concrete mix. This is due to the higher water absorption capacity of fine glass particles.
- To maintain workability, the use of plasticizers or adjustments to the water-cement ratio is recommended.

3. Water Tightness

- Using glass powder in amounts up to 20% improves the water tightness of concrete due to a denser microstructure and reduced porosity.
- When cement is replaced by 30%, water tightness deteriorates, which is attributed to increased porosity and microcracking.

4. Microstructure

- SEM analysis confirmed the uniform distribution of glass powder within the cement matrix and its positive influence on the structure of hydrates, which contributes to improved strength and density of the concrete.
- At high glass powder contents, areas with increased porosity and structural heterogeneity were observed.

5. Alkali-Silica Reaction (ASR)

- The chemical composition of the glass powder contains amorphous silicon dioxide, which is potentially reactive in ASR.
- Visual inspection and sample analysis showed no significant microcracking, indicating a minimal risk of ASR when using finely ground glass powder in the specified dosages.

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