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Article

Investigation of the properties of fly ash and slag-based geopolymer concrete containing waste glass aggregates

Zhuzimkul Urkinbayeva[1], Assel Jexembayeva[2], Marat Konkanov[3], Samal Akimbekova[1], Lailya Zhaksylykova[4], Tariq Umar[5]

[1]Department of Technology of Industrial and Civil Engineering, L.N. Gumilyov Eurasian National University, Astana, Kazakhstan

[2]Department of Innovative Development, L.N. Gumilyov Eurasian National University, Astana, Kazakhstan

[3]Department of Innovative Development, L.N. Gumilyov Eurasian National University, Astana, Kazakhstan

[4]Department of Architecture, L.N. Gumilyov Eurasian National University, Astana, Kazakhstan

[5]School of Architecture and Environment, University of the West of England, Bristol, United Kingdom

*Correspondence: sammi_ok@mail.ru

Abstract. This paper evaluates the geopolymer concrete produced using industrial waste and waste glass obtained by crushing glass materials. Geopolymer concrete mixtures were prepared with a water-to-binder ratio of 0.35 and an alkali activator solution to binder ratio (AAS/B) of 0.5 and 0.4. The partial substitution of sand by waste glass was 10%, 20% and 30%. Laboratory results showed that the compressive strength of geopolymer concrete increased with the addition of waste glass for a geopolymer concrete with AAS/B = 0.5, but decreased for AAS/B = 0.4. The expansion due to the alkali-silica reaction (ASR) was below 0.1% which is the expansion limit. The shrinkage of geopolymer concrete during drying decreases with an increase in glass content. The results of this study indicate that using glass as a partial sand substitute in geopolymer concrete provides sufficient mechanical properties. In addition, the production of this concrete will improve environmental conditions by reducing the extraction of raw materials and recycling waste glass.

Keywords: geopolymer concrete, industrial waste, waste glass aggregate, alkali-silica reaction, alkali activator solution.

1. Introduction

Geopolymer concrete is an alternative construction material to traditional Portland cement concrete, made by activation of aluminosilicate materials such as fly ash, slag, silica fume, and metakaolin using the alkaline solution [1]. Geopolymerization is a reaction process among aluminosilicate materials and alkali metal silicates, resulting in the formation of a strong polymer [2]. The final state performance of the geopolymer concrete depends on the type of constituents used in the mixture, including binder material, activators, aggregates, and required admixtures. The tectoluminosilicate type of three-dimensional structure in the geopolymer grid provides nanoporous characteristics, allowing chemically and physically bound water molecules (hydroxyl groups – OH) to evaporate when heated [3]. This property prevents the boiling of water and the destruction of concrete from the inside, as happens with Portland cement. In this regard, the strength of the geopolymer concrete obtained from the experiment will be comparable to that of traditional cement-based concrete. The main advantages of geopolymer concrete are lower CO_2 emissions, fire and corrosion resistance, reduction of raw materials usage, recycled industrial waste, and cost savings [4].

The continuously increasing demands for enhancing environmental sustainability and energy efficiency in the construction materials industry, along with the growing emphasis on waste utilization, drive intensive research in the development of binding materials that incorporate waste from the fuel industry [5]. Construction activities are the most materials-intensive human endeavors. Each year, billions of tons of mineral raw materials are extracted from the natural environment to produce traditional cement-based concrete and other building materials. Global cement production is approximately 3.5 billion tons per year [6]. Moreover, cement production is one of the issues of global carbon dioxide (CO_2) emissions, taking a part of approximately 7% [7]. Therefore, it is extremely important to partially replace traditional concrete production with geopolymer concrete, which utilizes industrial waste in order to reduce raw materials extraction and CO_2 emission [8]. However, the application of industrial waste might negatively affect the performance of the concrete. For example, the excessive use of fly ash, slag, and silica fume might reduce the strength of the geopolymer concrete due to the segregation compared to the Portland cement concrete [9]. Another global concern is that large quantities of glass are discarded in landfills each year. In addition, sand remains the primary natural resource for concrete production. To address this issue, waste glass can serve as a substitute for sand, thereby reducing global sand consumption [10].

Geopolymer concrete has lower workability compared to the Portland cement-based concrete [11]. Moreover, the increase of slag compared to fly ash decreases the workability. However, it was investigated that the inclusion of slag helps to increase the strength of geopolymer concrete, making it reasonable to use the combination of fly ash and slag to produce geopolymer concrete. Furthermore, it was found that the application of NaOH solution with a molarity of 10M is better than 8M for durability of geopolymer concrete [12]. The source of fly ash also has an impact on the compressive strength due to the different particle size distribution and microstructure [13]. Usage of glass in concrete production leads to material cracking due to the expansion caused by alkali-silica reaction (ASR) [14]. In this case, the utilization of fly ash and slag can reduce the potential expansion.

There are many studies focused on fresh properties and compressive strength of geopolymer concrete, but few research works were done on the alkali-silica reactivity of geopolymer concrete containing waste glass aggregate. Therefore, there is a need to investigate and find optimal geopolymer concrete mixtures containing glass materials.

Since glass has similar characteristics to sand, such as chemical composition and physical properties, it can be hypothesized that waste glass can be incorporated as a partial sand replacement material in the production of geopolymer concrete [15].

The goal of this article is to use industrial byproducts and glass waste to identify the optimal mixture proportions to produce geopolymer concrete with acceptable strength and durability performances that can be used in the construction industry.

2. Methods

Seven different mixture compositions were prepared to determine the effect of two variables, such as glass and alkaline activator solution content, on the performance of concrete based on the previous studies [16]. The proportions of each material are presented in Table 1. A binder material consisting of 60% fly ash and 40% slag was used, with partial replacement of sand by glass waste in the proportions of 0%, 10%, 20%, and 30%. For all mixtures, the water-to-binder ratio was set at 0.15. However, the ratio of the alkaline activator solution to the binder (AAS/B) varied between the two groups to analyze the effect of the alkaline activator solution concentration on the properties of geopolymer concrete [17]. For the first four mixtures, the AAS/B value was set at 0.5, while for the remaining three mixtures, it was set at 0.4. The molarity of NaOH for all 8 mixtures was 10M. Sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) were used as alkaline activators since application of these solutions results in the formation of a strong bond between binder and aggregates [18].

Table 1 – Proportions of Geopolymer mortar mixtures, kg/m^3

Mixtures	Fly ash	Slag	Sand	Glass	Na_2SiO_3	NaOH	Plast	Water
GPC 0.5-0	556.7	371.1	397.6	-	309.0	44.2	12.1	95.42
GPC 0.5-10	556.7	371.1	357.8	39.8	309.0	44.2	12.1	95.42

GPC 0.5-20	556.7	371.1	318.1	79.5	309.0	44.2	12.1	95.42
GPC 0.5-30	556.7	371.1	278.3	119.3	309.0	44.2	12.1	95.42
GPC 0.4-10	569.2	379.4	365.9	40.7	253.0	36.1	12.1	146.3
GPC 0.4-20	569.2	379.4	325.3	81.3	253.0	36.1	12.1	146.3
GPC 0.4-30	569.2	379.4	284.6	122.0	253.0	36.1	12.1	146.3

Note: 0.5 and 0.4 are the content of AAS/B; 0, 10, 20, and 30 are the fraction of glass in %.

Energy Dispersive Spectral (EDS) analysis was conducted using the 5EDX9000V spectrometer, model 200-ES1202344536, 220V 50/60Hz, to determine the chemical composition of fly ash, slag, sand, and glass [19]. This test is required to analyze the distribution of chemical compounds and define the validity of using industrial by-products and waste glass as aggregates to produce geopolymer concrete. The results of the chemical composition analysis test are presented in Table 2. The main components of the glass material are silica oxide (71.86 %), sodium oxide (10.84 %), and calcium oxide (12.96 %) [20]. Since the major portion of chemical compounds in glass is silica, as well as in sand, the results justify the application of glass as a partial sand substitution material.

Table 2 – Chemical Composition of Fly ash, Slag, Sand, and Glass [%]

Waste	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	MgO	TiO_2	Na_2O	K_2O	MnO
Fly ash	60.55	28.12	6.74	5.59	0.04	0.65	1.05	0.42	0.19	0.09
Slag	61.46	28.34	5.37	5.62	0.04	1.69	1.29	0.48	1.17	0.09
Sand	49.79	14.33	6.52	13.60	0.56	0.75	0.84	4.53	3.16	0.28
Glass	71.86	2.530	0.64	12.96	0.04	0.55	0.12	10.84	0.31	0.04

Fly ash is the non-combustible residue that forms from the mineral impurities in fuel during its complete combustion. The chemical composition of fly ash is primarily represented by four elements: aluminium (Al), silicon (Si), calcium (Ca), and, in smaller amounts, iron (Fe). River sand is a type of rock formed by the erosion of hard minerals. Its chemical formula is SiO_2, or silicon dioxide [21]. Depending on the chemical composition of the slag melts, the rapidly cooled slags develop an amorphous structure. This prevents the formation of a crystalline structure and makes the slag a reactive material with better bonding properties. The chemical composition of blast furnace slags is primarily represented by four oxides: CaO, MgO, Al_2O_3, and SiO_2, with iron oxides present in small quantities.

Sand and waste glass were sieved to determine the size distribution and use the particular amount of each size during the mixing process of geopolymer concrete.

The process of preparing samples and conducting tests began with the preparation of the alkaline activator solution 24 hours before mixing the geopolymer concrete [22]. On the mixing day, all materials were combined using a laboratory mixer. Initially, the binder materials were mixed for 60 seconds, followed by the addition of the alkaline activator solution, which was mixed for 120 seconds. The mixture was then stirred for another 240 seconds while incorporating fillers. A 90-second pause was taken to scrape off any material adhering to the walls of the mixing bowl. Finally, all components were mixed again for an additional 150 seconds. Once the mixing process was complete, the fresh homogeneous mixture was poured into molds of different sizes, depending on the specific tests. After 24 hours, the samples were demolded and left to air dry at room temperature and about 45% of relative humidity until the testing day.

Compressive strength, ASR, and drying shrinkage tests were done to determine the mechanical and durability properties of the geopolymer concrete samples. All of these tests were done according to the standards of the American Society for Testing and Materials (ASTM).

The compressive strength test was done based on [23]. For this test, 50 mm cube samples were cast and cured at room temperature. These samples were tested using the universal testing machine on the 7th, 14^{th,} and 28th day [24].

The ASR test was done following [25]. Four bar samples, each measuring 25×25×285 mm, were prepared for each mixture and left air cured at room temperature for one day. After curing, the samples were immersed in water-filled containers, which were then placed in an oven at 80 ± 2 °C for 24 hours. Subsequently, the initial length of all samples was recorded as the 0-day measurement. The samples were then transferred to a container containing a 1M NaOH solution and again stored at 80 ± 2 °C to investigate the effect of a harsh environment on the length change and potential cracking [26]. Measurements were taken at 3- and 4-day intervals up to the 28th day to assess the relative expansion of geopolymer concrete.

The drying shrinkage test was done based on [27]. For each mixture, bar samples with a size 25x25x285 mm were cast and cured at room temperature and relative humidity approximately equal to 45% [28]. Every 3- and 4-day interval for 3 months, the length change and weight loss of each sample were measured to analyze the moisture loss and the effect of glass particles on the performance of geopolymer concrete.

3. Results and Discussion

The results of compressive strength tests for each geopolymer mixture aged 7, 14, and 28 days are demonstrated in Figure 1.

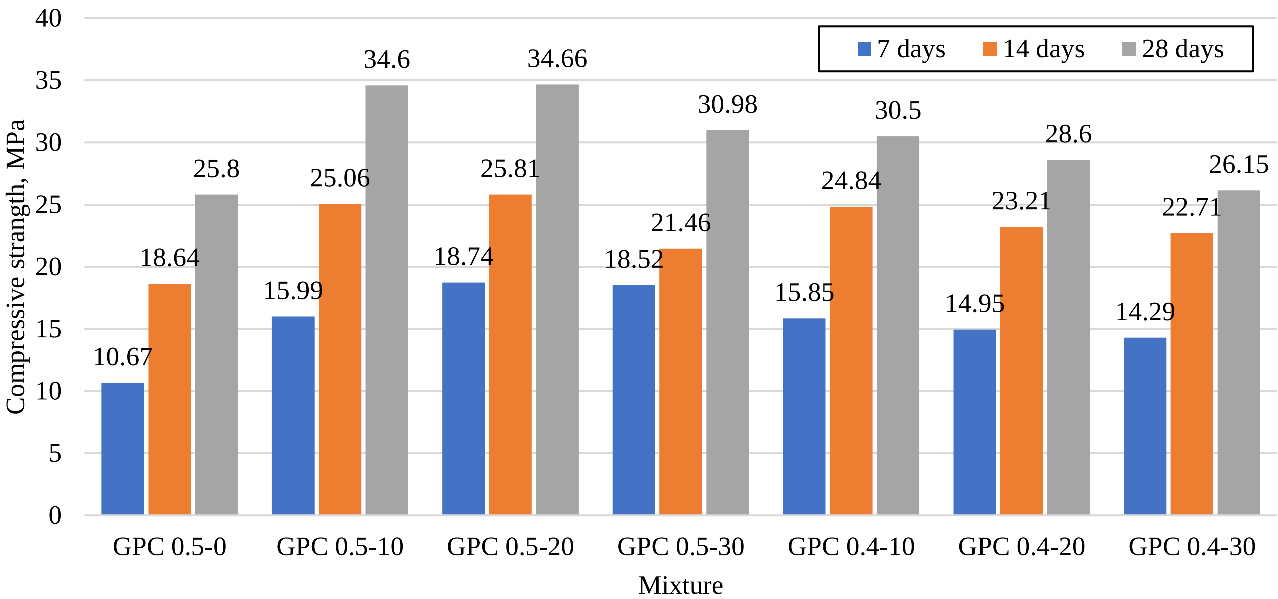

Figure 1 – Compressive strength of geopolymer concrete

Based on Figure 1 above, the compressive strength of each geopolymer concrete increases after a certain period of time. With the ratio AAS/B = 0.50, the mixtures containing waste glass demonstrated higher compressive strength compared to the control mixture with a 0% glass content, which explains the improved gel mesh of the geopolymer system due to dissolved silica particles in an alkaline medium [29]. With the same AAS/B = 0.50 ratio, geopolymer mixtures containing 10 % and 20 % glass exhibited the same maximum strength of approximately 35 MPa after 28 days; however, both showed unequal compressive strengths at 7 and 14 days. Further increasing the glass content to 30 % slightly reduced the compressive strength of the geopolymer mixture to about 31 MPa, which may be attributed to poor bonding between the glass and the binder at high glass content due to the smooth surface of the glass. Therefore, even though the addition of glass increases the strength at lower glass content, the further increase of glass to approximately higher than 20% sand replacement has a negative effect on the performance of geopolymer concrete.

Additionally, the test results indicated a negative impact of reduced alkali-activated solution (AAS) content in the mixture on the strength development of geopolymer concrete. For instance, the

GPC0.4-10 mixture, containing 10% glass, exhibited lower compressive strength after 28 days compared to the GPC0.5-10 mixture with the same glass content (30.5 MPa vs. 34.6 MPa). In fact, the silica and alumina contained in fly ash and slags primarily contribute to an increase in the strength properties of the geopolymer mixture due to the reactivity of the components. The concentration of AAS affects reactivity. At lower AAS concentrations, silica and aluminum monomers are released to a lesser extent, and the aluminosilicate reaction occurs weakly, resulting in reduced geo-polymerization due to poor gel formation, which is essential for strengthening and enhancing the material's strength [30]. Similarly, in the case of 0.5 AAS/B, increasing the glass content to 20 % and 30 % led to a decrease in strength to 28.6 MPa and 26.2 MPa, respectively.

Figure 2 shows the expansion behavior of geopolymer concrete mixtures subjected to ASR.

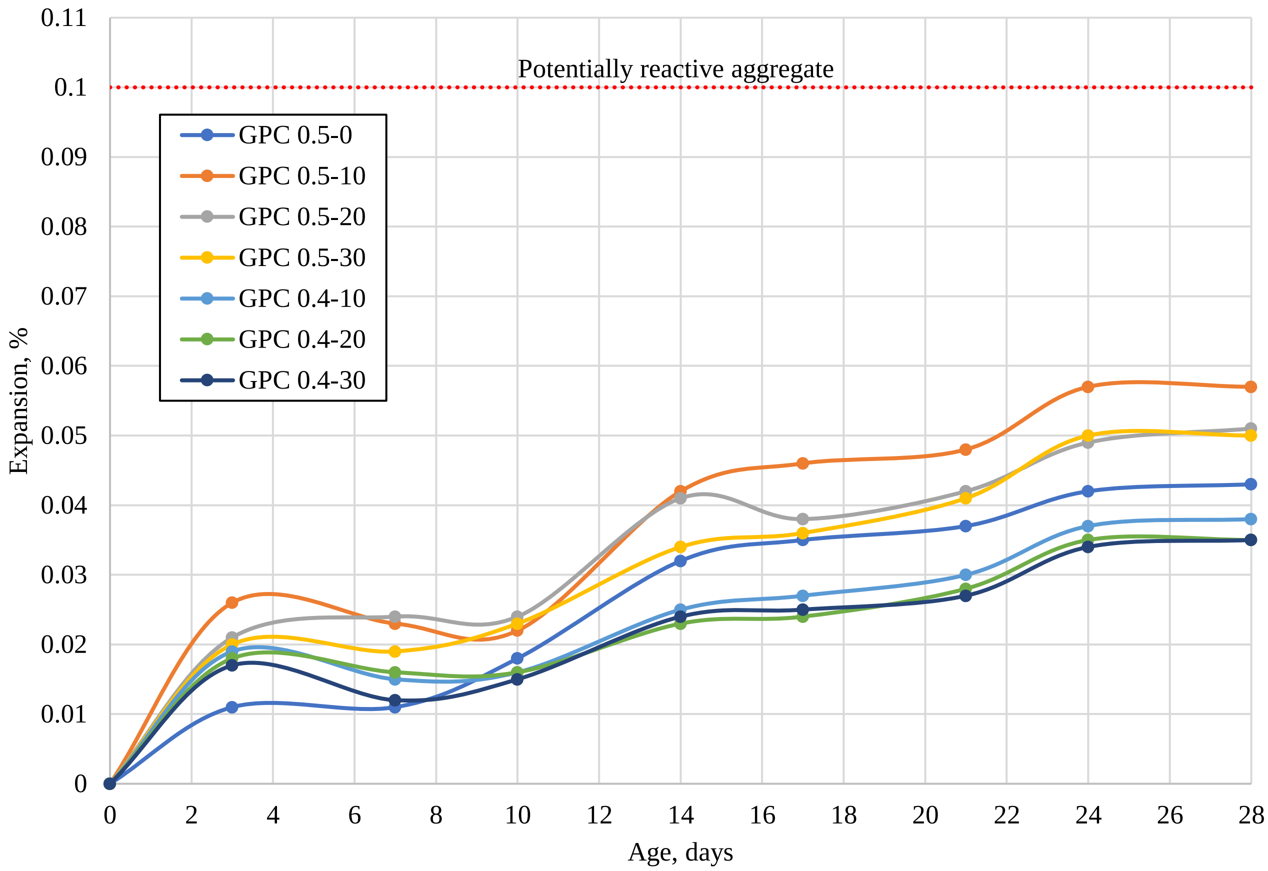

Figure 2 – ASR of geopolymer concrete

As shown in Figure 2 above, regardless of the AAS/B ratio and the WGS replacement percentage, all geopolymer concrete mixtures exhibit minimal expansion, significantly lower than the 0.1% threshold set by [31] for potentially reactive aggregates. These results align with investigations of [32], where the mechanisms responsible for mitigating ASR expansion in geopolymer concrete containing fly ash and slag are investigated. The amorphous components in fly ash and slag consume a substantial portion of the alkalis in the pore solution, transforming them into cementitious binders. This process reduces alkali concentration through dilution and fixes alkalis within the hydration reaction, thereby limiting the formation of ASR gel compared to ordinary Portland cement-based concrete.

Furthermore, increasing the waste glass content does not considerably increase the expansion due to the ASR. This may be attributed to the influence of fly ash and slag, which lower the alkali content in the binder and promote the formation of non-expansive lime-silica gel, as the silicate components in glass contribute to geopolymerization [32]. The ASR test results confirm that fly ash and slag-based geopolymer concrete effectively controls expansion in mixtures containing waste glass aggregates, as none exceeded the 0.1% expansion limit.

Figure 3 shows the drying shrinkage of the geopolymer mixtures.

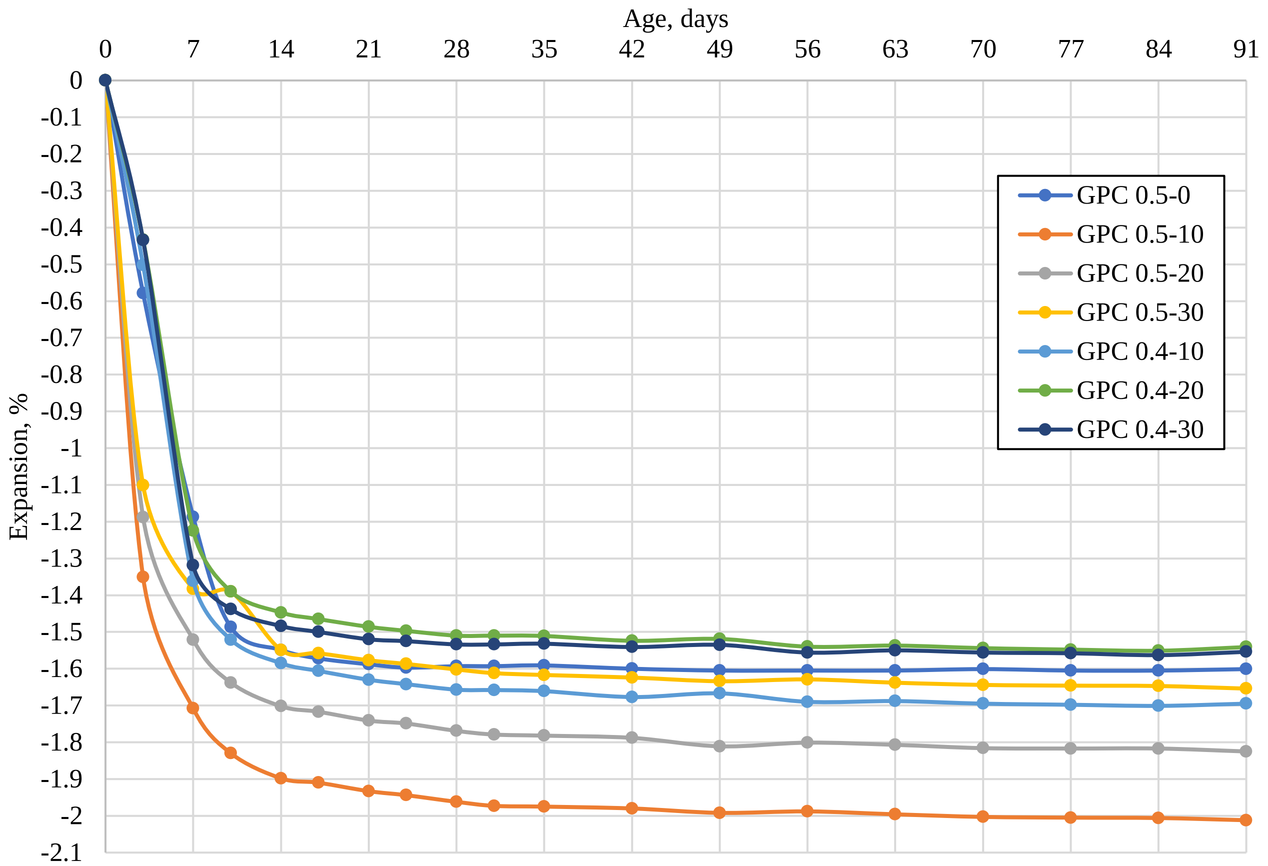

Figure 3 – Drying Shrinkage of geopolymer concrete

As shown in Figure 3 above, the GPC0.5-10 mixture experienced the highest shrinkage, with a length change of – 2.03 % by day 91. Increasing the glass content reduced the drying shrinkage of the geopolymer mixture, regardless of the different AAS/B values. The decrease in shrinkage during drying due to an increase in the filler content in the glass is explained by the reduced water absorption capacity of the glass. However, the geopolymer mixture containing 100 % sand had a lower shrinkage during drying compared to GPS 0.5-10.

Studies have confirmed that mixtures of geopolymers with AAS/B = 0.50 showed greater shrinkage during drying than those with AAS/B = 0.40. This is explained by the increased tensile stress in the capillary pores of the geopolymer mixture, which contributes to higher shrinkage during drying [33].

4. Conclusion

In this study, the chemical properties of cementitious materials and aggregates and the mechanical properties of geopolymer concrete produced by partially replacing sand with glass were obtained. When the ratio of the alkaline activator solution to binder is 0.50, the addition of glass enhances the compressive strength. However, at AAS/B = 0.40, the inclusion of glass reduces compressive strength. The application of fly ash and slag helps to maintain the expansion of geopolymer concrete with glass due to the ASR below 0.1%. Regardless of the alkaline activator to binder ratio, the gradual increase in glass content decreases the drying shrinkage of the geopolymer mixture.

Overall, the use of large quantities of local industrial and solid municipal waste, such as fly ash, blast furnace slag, and glass, will contribute to environmental protection. These materials can be used to produce geopolymer concrete with a cement-free binder that achieves a compressive strength of 35 MPa without thermal treatment. Utilizing glass as a sand replacement material is reasonable, as geopolymer concrete containing glass exhibits adequate strength and durability properties. This geopolymer concrete can be used as a construction material for small buildings, statues, and paving with lower loads.

This study has some potential limitations. The limited number of mixture types and conducted tests does not show the full scale of durability properties of geopolymer concrete. Therefore, there is a need to conduct more laboratory work to evaluate and determine the full potential of geopolymer concrete with waste glass.

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Information about authors:

Zhuzimkul Urkinbayeva – Senior Lecturer, Department of Technology of Industrial and Civil Engineering, L.N. Gumilyov Eurasian National University, Astana, Kazakhstan, zhuzim.isina@mail.ru
Assel Jexembayeva – PhD, Director, Department of Innovative Development, L.N. Gumilyov Eurasian National University, Astana, Kazakhstan, jexembayevaassel@gmail.com
Marat Konkanov – PhD, Director, Science and Production Centre "ENU-Lab", L.N. Gumilyov Eurasian National University, Astana, Kazakhstan, marcon@metrology.kz
Samal Akimbekova – PhD Student, Department of Technology of Industrial and Civil Engineering, L.N. Gumilyov Eurasian National University, Astana, Kazakhstan, sammi_ok@mail.ru
Lailya Zhaksylykova – MSc, Acting Associate Professor, Department of Architecture, L.N. Gumilyov Eurasian National University, Astana, Kazakhstan, sabyrbayeva_la@enu.kz
Tariq Umar – PhD, Professor, School of Architecture and Environment, University of the West of England, Bristol, United Kingdom, tariqumar1984@gmail.com

Author Contributions:
Zhuzim Urkinbaeva – concept, methodology, testing, drafting.
Assel Jexembayeva – resources, funding acquisition.
Marat Konkanov – resources, funding acquisition.
Samal Akimbekova – data collection, analysis, editing.
Lailya Zhaksylykova – modeling, visualization.
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