Waste-to-Resource Preparation of Geopolymers Containing Glass Foam Derived from Hazardous Glass Waste

Thesis booklet of the PhD dissertation

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1. Introduction

As regulations to protect the environment become stricter, more and more people are interested in using green and environmentally friendly materials [1, 2]. For the construction of new buildings, the maintenance of buildings, and technical infrastructure, the construction industry requires a significant amount of natural aggregates and cement. However, the extensive use of these natural resources is causing a gradual depletion of the Earth's reserves, potentially leading to environmental degradation. Researchers are dedicated to discovering and developing new environmentally beneficial substances.

Glass waste represents a significant amount of solid waste. According to the EU Action Plan, the recycling rate for glass waste must reach at least 85 % by 2030 [3]. In this respect, producing foam glass represents an excellent opportunity to recycle large amounts of glass waste. It is well known that foam glass, produced by mixing waste glass powder with a foaming agent and then heating the mixture above the softening point of the glass, is used as a thermal and acoustic insulation material in construction and road building. The number of studies on the development of glass foam has increased in the last decade [4].

In recent years, cement production has increased extraordinarily worldwide. It is the third-largest contributor to anthropogenic CO_2 (carbon dioxide) emissions. Each one ton of calcium carbonate used in cement production generates 0.44 tons of CO_2 [5, 6]. The construction industry will face future challenges in adopting alternative building materials to replace cement. Geopolymers (GPs) are currently being introduced to fully substitute ordinary Portland cement (OPC) in concrete production [6, 7]. GP is the name given to this innovative binder material. In terms of the environment, the main advantage of geopolymer is that it can reduce CO_2 emissions into the atmosphere by about 80-90% compared to OPC and lower energy consumption during production [7, 8].

Lightweight geopolymers (LWGPs) have emerged as a revolutionary class of materials that promise significant advancements in sustainable construction. When formulated as lightweight materials, geopolymers not only reduce the structural weight of buildings but also offer superior thermal insulation and fire resistance [9]. These properties contribute to lower energy consumption in heating and cooling buildings, further amplifying their environmental benefits. When FGA is used as a lightweight aggregate made from glass waste, making lightweight geopolymers will be a key component in the transition towards more sustainable and energy-efficient construction practices.

2. Literature review

Theoretical background and literature concerning the production process and the influencing factors associated with lightweight structures, foam glass aggregates, and geopolymer binders.

2.1 Lightweight structure

Lightweight structure, a promising structural material, possesses numerous advantages. These include diminished dead load on structures, enhanced thermal and sound insulation characteristics, ease of handling and transport, and reduced construction expenses. Consequently, it finds diverse applications, such as flooring in steel-framed buildings, parking structures, bridge decks, girders with specified-density concrete, lightweight prestressed concrete, etc. [10].

2.2 Lightweight aggregate

Lightweight aggregate is typically described as any aggregate with a bulk density of under 1.2 g/cm³ and a uniaxial compressive strength of more than 1 MPa [11,12]. The advantages of lightweight aggregates are:

- Reduced weight is their ability to reduce the overall weight of structures.
- Improved insulation can enhance the insulation properties of materials, making them suitable for applications where thermal efficiency is important.
- Ease of handling due to their lower density and light weight.

2.3 Foam glass aggregate

Foam glass aggregate (FGA) is produced from over 98 wt.% waste glass and less than 2 wt.% foaming agents, playing an important role in waste management technology. The problem of waste glass involves the difficulty of managing and recycling substantial amounts of discarded glass, which frequently ends up in landfills, contributing to environmental pollution and resource depletion [13]. Recycling waste glass into new glass products is often prohibitively expensive due to high processing costs. However, repurposing waste glass into valuable products like foam glass aggregate offers a more cost-effective and environmentally friendly solution. The advantages of FGA can be utilized in many types of civil engineering structures, providing thermal insulation and frost protection, reducing vertical and lateral earth pressures, and enhancing slope stability.

2.4 Geopolymer

The term 'geopolymer' was introduced in the 1970s by French scientist and engineer Professor Davidovits. It refers to a class of solid materials created through the chemical reaction between an aluminosilicate powder and an alkaline solution. Geopolymers are inorganic materials with

a polymeric molecular structure, offering exceptional strength and a variety of unique properties [14,15]. Geopolymer binder is an environmentally superior alternative to OPC for several reasons. It is produced at lower temperatures, significantly reducing greenhouse gas emissions [16,17].

2.5 Knowledge gap

The knowledge gaps for this research are categorized into three parts based on the experimental plan: the preparation of foam glass aggregates, the development of metakaolin-based geopolymer, and the preparation of lightweight geopolymer. Each part was designed depending on the scientific gap and to enhance it.

- **Knowledge gaps for prepared foam glass aggregate**
  1. Many researchers used CRT-GW to prepare foam glass used in different applications. In contrast, this work is the first investigation to apply foam glass prepared from CRT-GW as a lightweight aggregate in a geopolymer matrix.
  2. Based on the literature, foam glass derived from CRT-GW was synthesized using various foaming agents, yet the temperature range for the foaming process remained unspecified. In this study, silicon carbide (SiC) was employed as the foaming agent, and the temperature range required for the foaming process was determined by inspecting the mixture by heating microscopy.
  3. Some researchers focused on leaching tests to check if the foam glass made from CRT-GW is safer, while others focused on measuring physical and mechanical properties. The knowledge gap in this work is to study the effects of foaming temperatures on all physical, mechanical, and thermal properties and the leaching test for hazardous elements.
- **Knowledge gaps for the development of metakaolin-based geopolymer**
  1. The effect of a wide range of 0 to 100 wt.% water glass in the activator solution for metakaolin-based geopolymer on the occurrence of efflorescence and the change in composition, microstructure, bulk density, volume shrinkage, the average value of compressive strength of and thermal conductivity is studied.
  2. Many researchers aim to prepare geopolymer binders that harden (set) at room temperature and have a suitable setting time by using various additives. In this work, I have focused on controlling the factors that affect the properties of geopolymer binders to achieve this goal, including the water glass/sodium hydroxide ratio and the solid-to-liquid ratio.

- **Knowledge gaps for the preparation of lightweight geopolymer**

  As far as it concerns using foam glass aggregate with geopolymer binder, one scientific paper, by Kristaly et al [18], used foam glass aggregate made from bottle waste with fly ash-based geopolymer. In this new work, I used foam glass aggregate derived from CRT-GW with metakaolin-based geopolymer.

2.6 Objectives

The main objectives of this work are:

- To produce CRT-GW glass foams ("*lightweight aggregates*") with optimized foaming temperature to decrease energy consumption.
- To encapsulate the CRT lightweight aggregates (*LWAs*) into a metakaolin (MK)-based geopolymer matrix to produce a new, environmentally friendly lightweight building material (*lightweight geopolymer concrete, LWGPC*) by eliminating the hazardous glass waste.
- To optimize the curing conditions of the LWGPC to save energy. To investigate the effect of LWA in the geopolymer matrix with physical, mechanical, thermal, and microstructural tests.

3. Materials and Methods

3.1 Main raw materials

The raw materials were used to produce foam glass aggregate:

- Cathode ray tube glass waste was taken from dismantling old televisions and computer monitors. Mishandling CRT waste can lead to the release of toxic substances into the environment, making it essential to manage these materials with care.
- Silicon carbide as a foaming agent, provided by Ibiden Hungary Ltd.
- Methylcellulose – A chemical compound derived from cellulose was used as a binder by dissolving 0.5 g of methylcellulose in 50 ml of distilled water.

The raw materials were used to prepare the geopolymer binder:

- Kaolin is a white mineral clay primarily composed of the mineral kaolinite. It is a soft, earthy material supplied by Interkeram Ltd. in Hungary.
- Water glass, also known as sodium silicate (Na_2SiO_3), is a chemical compound made from sodium oxide (Na_2O) and silicon dioxide (SiO_2). It is a viscous liquid (solution).
- A 10 M sodium hydroxide solution was prepared by dissolving NaOH flakes (purity: 98%) in distilled water.

3.2 Experimental work

The experimental work includes three parts: 1) preparation of foam glass aggregate, 2) preparation of geopolymer binder and statistical analysis, and 3) preparation of lightweight geopolymer.

3.2.1 Preparation of foam glass aggregate

CRT glass waste was pulverized and ground using a RETSCH PM 400 planetary ball mill using agate balls and jars for 1 hour at 200 rpm. A mixture of 99 wt.% CRT glass waste powder and 1 wt.% silicon carbide was prepared. A binder made of methylcellulose dissolved in distilled water was used to form a dough that could be hand-shaped into small pellets. The dough was prepared by dissolving 1 g of methylcellulose in 100 ml of distilled water and then thoroughly combining this solution with 200 g of the powder. For measuring thermal conductivity and volume expansion, cylindrical specimens with a diameter of 15 mm were prepared.

The prepared pellets were then subjected to a heating process in a programmable furnace at four different foaming temperatures: 725 °C, 750 °C, 775 °C, and 800 °C, with a holding time of 10 minutes and a heating rate of 360 °C per hour. These temperatures were selected based on a heating microscope analysis. After the heating cycle, the pellets were left to cool to room temperature in the furnace, as shown in Figure 1.

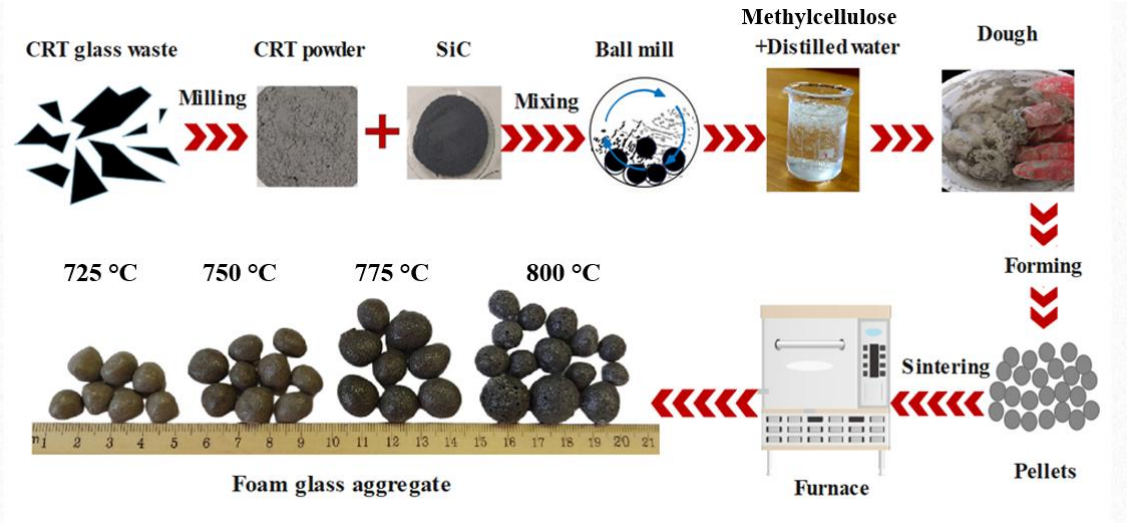


Figure 1. Flowchart for the preparation of foam glass aggregate.

3.2.1 Preparation of metakaolin-based geopolymer

After the calcination of kaolin at 750 °C for 3 hours, metakaolin (MK) was formed and ground using a ball mill (Retsch PM 400) with agate balls at 180 rpm for 20 minutes. Five agate balls of different sizes (the diameter of three balls was 1.5 cm and the other two balls were 3 cm) were used. To prepare the NaOH solution, 400 g of sodium hydroxide flakes were dissolved in 1 L of distilled water, resulting in a concentration of 10 M NaOH solution. The influence of the

water glass to sodium hydroxide ratio on the properties of the geopolymer binder was investigated. The alkaline activator solutions were prepared by mixing water glass and sodium hydroxide solution with five different dosages (0, 25, 50, 75, and 100 wt.%) of water glass. The solutions were mixed with a blender at 400 rpm for 3 minutes. The MK powder was mixed with the alkaline activators in the blender at 300 rpm for 3 minutes and at 480 rpm for 2 minutes. The fresh geopolymer paste was poured into cubic silicon moulds of 2.5 cm×2.5 cm ×2.5 cm and 5 cm×5 cm×5 cm geometry and cured at two different curing temperatures (60 ºC and 75 ºC) for 24 hours. The geopolymer sample preparation method is shown in Figure 2., while the mix design is shown in Table 1.

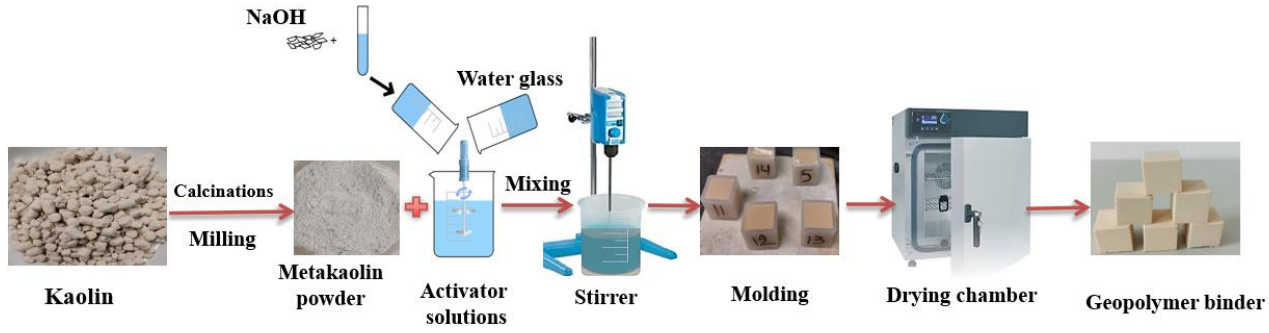


Figure 2. Scheme for the preparation of geopolymer samples.

Table 1. Composition of MK-GP with a L/S ratio of 1.1 and NaOH (10 M).

Samples codes	Liquid [wt.%]		Solid [wt.%]
	Water glass (g)	NaOH (g)	MK powder (g)
MK-GP0	0	100	90.9
MK-GP25	25	75	90.9
MK-GP50	50	50	90.9
MK-GP75	75	25	90.9
MK-GP100	100	0	90.9

The goal was to prepare a geopolymer at room temperature to be applied in work life. For this, the properties of geopolymers cured at room temperature were studied after selecting the best water glass percentage in the activator solution (at 50 wt.% water glass).

The lighter foam glass aggregate, with a density of 0.58 g/cm³, floated when combined with a geopolymer binder at a liquid-to-solid ratio of 1.1. To prevent this phenomenon, to improve the distribution of aggregates within the binder, and to enhance compressive strength, the impact of varying the liquid-to-solid ratio on the properties of the geopolymer was investigated.

MK-GP was prepared by mixing an equal weight percentage of water glass and sodium hydroxide solution to prepare the activator solution. The geopolymer binder samples were prepared using a silicon cubic mold with a length of 5 cm. At this time, the samples were cured at two different temperatures: 60 °C and room temperature and formulated with different

liquid-to-solid ratios of 0.8, 0.95, and 1.1. The geopolymer binder mix design is shown in Table 2.

Table 2. The composition of the geopolymer binder with a $NaOH/Na_2SiO_3$ ratio of 1 and NaOH with 10 mol/L

Sample code	L/S	Liquid (g)		Solid (g)
		Na_2SiO_3	NaOH	Metakaolin
MK-GP 0.8	0.8	50	50	125
MK-GP 0.9	0.9	50	50	111.1
MK- GP 1.1	1.1	50	50	90.9

3.2.3 Preparation of lightweight geopolymer

The lightweight geopolymer with foam glass aggregate (LWGP-FGA) was prepared cubic samples with a length of 5 cm by mixing 70 vol% of geopolymer binder and 30 vol% of FGA [19] (using this design, the bulk density estimates of LWGP-FGA less than 1.44 g/cm^3 according ASTM C 330 get a lightweight structure) for each, and the samples were hardened at room temperature. Figure 3. describes the procedure used to prepare the LWGP-FGA.

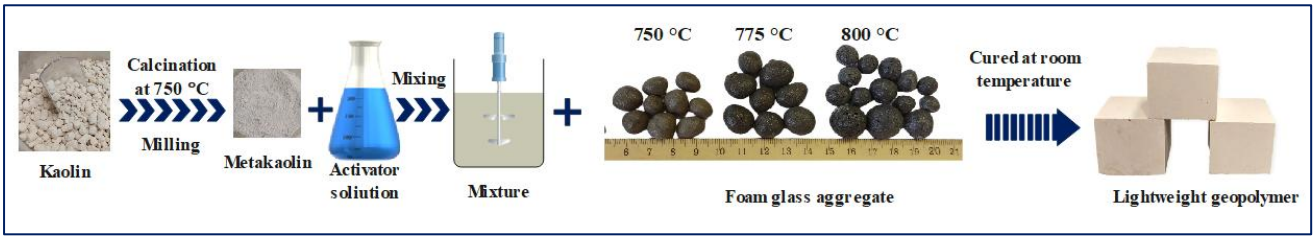


Figure 3. Sketch the preparation of LWGP-FGA.

4. Results and discussion

4.1 Characterisation of foam glass aggregate (FGA)

The bulk density and volume expansion results for FGA sintered at different temperatures are shown in Figure 4.

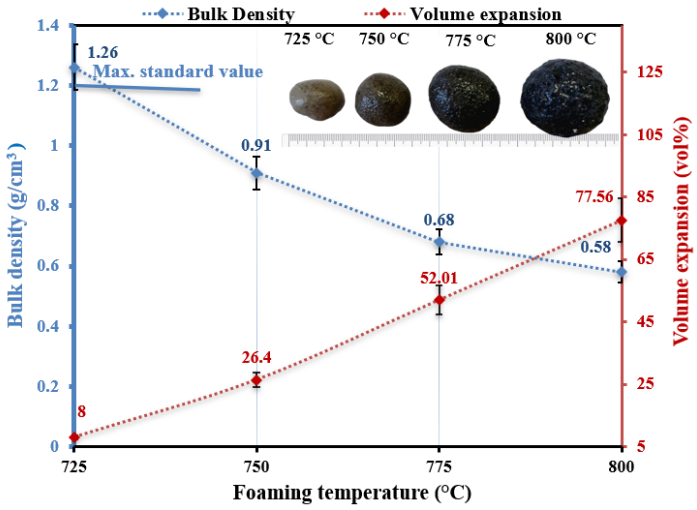


Figure 14. Volume expansion and bulk density for FGA at different foaming temperatures.

The volume expansion increased with the foaming temperature, while the bulk density decreased. The highest volume expansion value was 77.56 vol% for samples sintered at the maximum foaming temperature of 800 °C, while the lowest value was 8 vol% for samples sintered at 725 °C, at which the foaming process started. The foaming temperatures were selected depending on the heating microscopy results and the photographed image in Figure 44., the sample volume change. The bulk density of the lightweight aggregate used in concrete must be lower than 1.2 g/cm^3, according to EN 13055 standard [20]. The samples sintered at a temperature range of 750-800 °C have a range of bulk density of 0.91-0.58 g/cm^3, which is less than the standard limit, while the bulk density of the sample sintered at 725 °C was 1.26 g/cm^3 over the standard limit, so this sample was neglected for further investigations.

Figure 5. shows the microstructure of FGA.

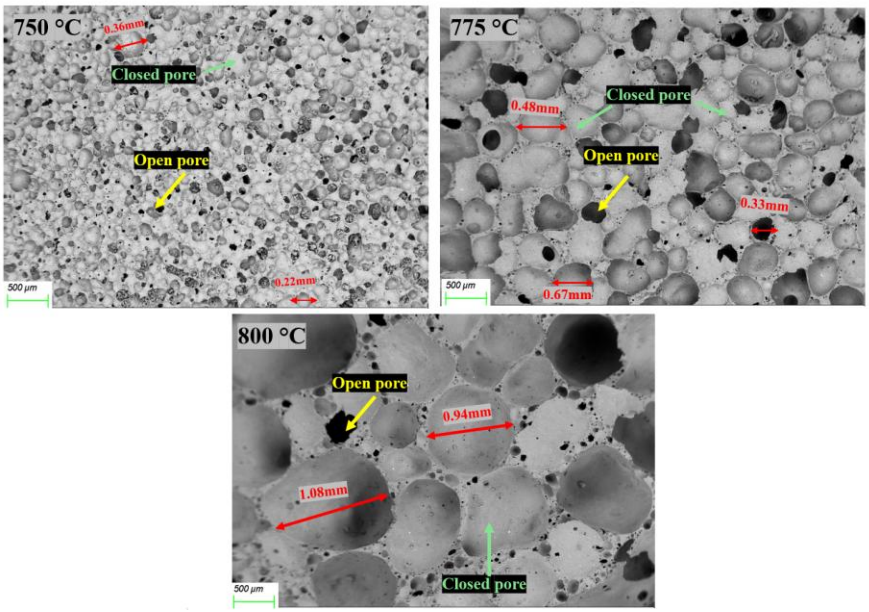


Figure 5. Microstructure of the FGA (scale bar=500 µm).

Many small open pores appeared in the samples sintered at 750 °C, while when the temperature increased to 775 °C and 800 °C, the pores expanded much more, and closed honeycomb-shaped pores were formed. The average pore size of FGA was 0.18 mm, 0.49 mm, and 0.98 mm for samples sintered at 750 °C, 775 °C, and 800 °C, respectively.

4.2 Characterisation of metakaolin-based geopolymer

4.2.1 Results and discussion of MK-GP with different dosages of water glass in the activator solution and cured at 60 °C and 75 °C

The analysis of the physical properties of MK-GP was performed after 28 days of curing. Curing conditions were: one day at 60 °C, and 75 °C, 27 days at room temperature. The volume shrinkage of the specimens was found to increase with increasing sodium-silicate (water glass)

content and curing temperature because these two reasons lead to chemical shrinkage in forming silica-rich gels and promote the formation of larger gel holes.

The results of bulk density and volume shrinkage tests of the geopolymer are shown in Figure 6.

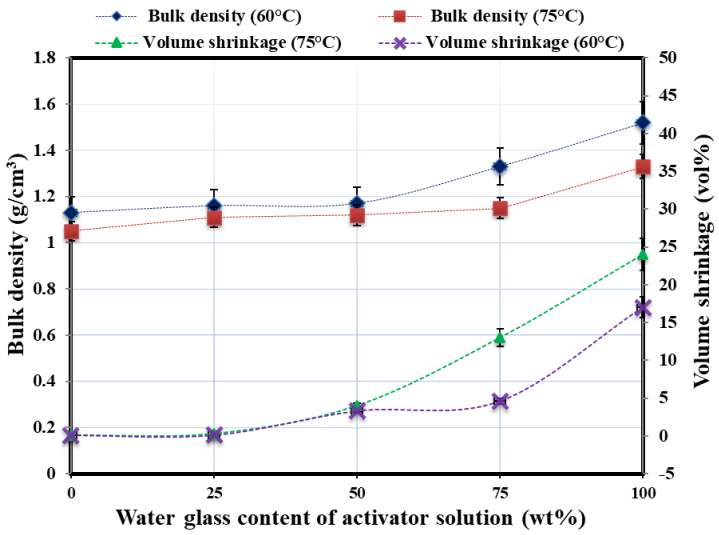
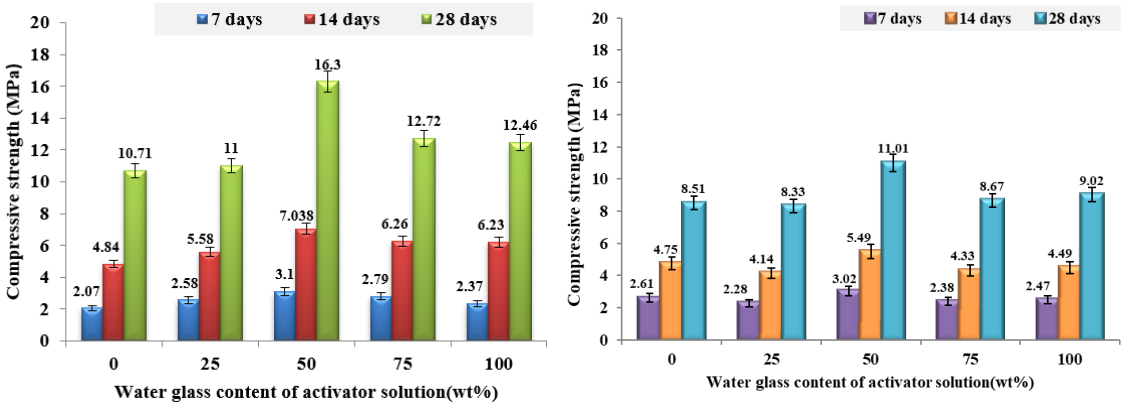


Figure 6. Bulk density and volume shrinkage of MK-GP with different dosages of water glass in activator solution, and cured at 60 °C and 75 °C.

The results of the progression of the compressive strength of MK-GP at different ages (*7, 14, and 28 days*) cured at two different temperatures, 60 °C and 75 °C, are shown in Figure 7.



(a) Curing temperature: 60 °C (b) Curing temperature: 75 °C

Figure 7. Compressive strength of MK-GP cured at (a) 60 °C and (b) 75°C for one day.

The influence of the curing temperature can be seen. Specimens cured at 60 ºC have higher compressive strength values with a range of 10.71-16.3 MPa after 28 days than those cured at 75 ºC with a range of 8.51-11.01 MPa. The compressive strength tends to decrease when the curing temperature is higher than 60 ºC due to the chemical shrinkage of the geopolymer gel increases with the increase of curing temperature and curing time, resulting in more gel holes and micro defects.

4.2.2 Results and discussion of MK-GP made with different liquid-to-solid ratios and cured at 60 °C and room temperature

The bulk density of the geopolymer binders in samples that were cured at two different temperatures and had different liquid-to-solid ratios was measured. As shown in Figure 8., the bulk density range of the binders cured at 60 °C for 24 hours was 1.172-1.295 g/cm^3, and that of the binders cured at room temperature was 1.213-1.42 g/cm^3.

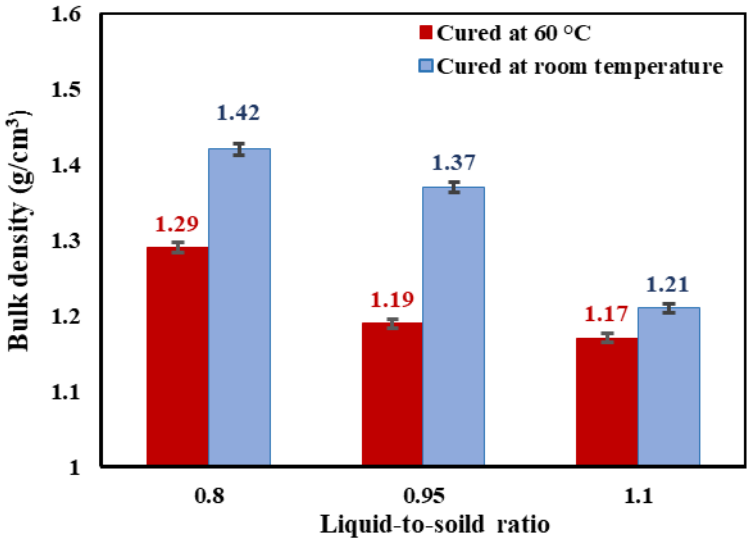


Figure 8. Bulk density of geopolymer binders with different liquid-to-solid ratios cured at two different temperatures.

In this work, the metakaolin-based geopolymer achieved its maximum compressive strength for samples cured at room temperature by adjusting the amount of the liquid-to-solid ratio and kaolin calcination temperature. The compressive strength of the geopolymer binders cured for 28 days is presented in Figure 9.

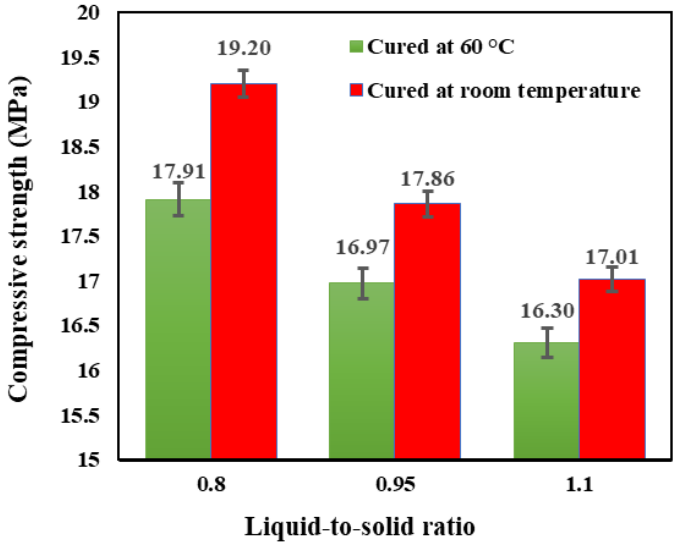


Figure 9. Compressive strength of geopolymer binders with different liquid-to-solid ratios cured at two different temperatures.

4.3 Characterisation of lightweight geopolymer with foam glass aggregate (LWGP-FGA)

Figure 10. shows the results of the bulk density and compressive strength for LWGP-FGA. The samples were measured after 28 days and cured at room temperature. LWGP-FGA had a bulk density range of 1.17-1.29 g/cm^3 and a compressive strength range of 8.02-19.2 MPa. These values comply with the requirements of LWC to classify the second group as "*Structural/Insulating"*. A big reduction was observed for compressive strength values reaching 53.18%, 52.56%, and 57.86% using FGA sintered at 750 °C, 775 °C, and 800 °C, respectively.

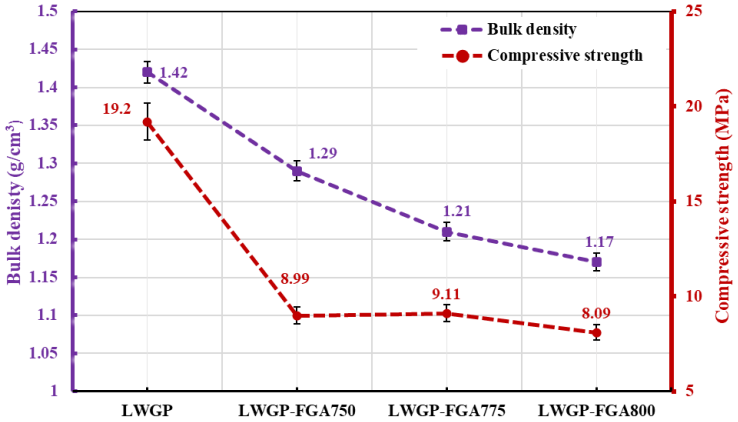


Figure 10. Bulk density and compressive strength results for LWGP-FGA.

The compressive strength of LWGP-FGA depended mainly on different factors, such as the compressive strength of the FGA, the interfacial adhesion of the aggregate grain to the geopolymer binder and the strength of the geopolymer binder. The cut cross-section area for LWGP-FGA, the sample LWGP-FGA750, shows the adhesion failure between the FGA and geopolymer binder, which led to a weak contact surface around the FGA inside the geopolymer binder, therefore, the compressive strength was reduced (Figure 11.). The samples LWGP-FGA775 and LWGP-FGA800 show good binding between the geopolymer binder entered the FGA pores on the surface.

(A) LWGP-FGA750 **(B)** LWGP-FGA775 **(C)** LWGP-FGA800

Figure 11. The failure surface of concrete, which can be used to determine the quality of adhesion/bond between the aggregate and the binder.

5. New scientific results

Thesis 1: Preparation of foam glass aggregate from CRT glass waste

I have successfully produced foam glass aggregate from 99 wt.% of CRT glass waste (*chemical composition: **SiO_2**:55.90 wt.%, **PbO**:13.36 wt.%, **BaO**:10.20 wt.%, **Na_2O**:5.96 wt.%, **K_2O**:5.49 wt.%, **SrO**:1.51 wt.%, **Al_2O_3**:1.70 **others**: 5.88 wt.%*; *median particle size d_{50}=11 µm*), and 1 *wt.%* of SiC (*Mineral composition: Moissanite 6H: 83,2 wt.%, Moissanite 4H, syn: 16,8 wt.%; particle size d>1µm*) as foaming agent on different sintering (*foaming*) temperatures (*750 °C; 775 °C; 800 °C*) using 360 °C/h heating rate and 10 min holding time. Using the above parameters, glass foams with the physical properties given in **Table A** can be produced.

Table A. Properties of the foam glass aggregate derived from CRT glass waste.

Physical property	Foam glass aggregate sintered at			Standard value / Limit	Reference
	750 °C	775 °C	800 °C		
Bulk density (g/cm³)	0.91	0.68	0.58	> 1.2	EN 13055-1
Compressive strength (MPa)	5.31	3.6	1.55	<1	https://doi.org/10.1016/j.jobe.2022.105426
Volume expansion (vol%)	26.4	52.1	77.56	-	-
Apparent porosity (%)	64	72.8	76.8	-	-
Thermal conductivity (W/m·K)	0.083	0.075	0.063	0.065 -0.220	ASTM C 332– 07
Lead concentration (mg/L)	0.021	0.046	0.12	5	EN 12457-3:2004; WHO guideline
Barium concentration (mg/L)	9.31	4.05	2.09	100	EN 12457-3:2004; WHO guideline

Related publications: *Sarah Kareem Mohammed Al-Saudi, Robert Géber: Production of lightweight geopolymer concrete with foam glass aggregate derived from cathode-ray glass waste, Case Studies in Construction Materials, 2024. (Q1) https://doi.org/10.1016/j.cscm.2024.e03888*

Thesis 2: Effect of foaming temperature on the leaching of lead and barium in CRT foam glass

It was experimentally demonstrated that the leaching of lead from foam glass derived from CRT glass waste (*99 wt.% of CRT glass waste /chemical composition: **SiO_2**:55.9 wt.%, **PbO**:13.36 wt.%, **BaO**:10.2 wt.%, **Na_2O**:5.96 wt.%, **K_2O**: 5.49 wt.%, **SrO**:1.51 wt.%, **Al_2O_3**:1.70 wt.%, **others**: 5.88 wt.%; median particle size d_{50}=11 µm), and 1 wt.% of SiC /Mineral composition: Moissanite 6H: 83,2 wt.%, Moissanite 4H, syn: 16,8 wt.%; particle size d>1µm/*) increasing with foaming temperature. The lead concentration (*standard limit: 5 mg/L*) more than doubled when the foaming temperature increased from 750 °C to 775 °C, and

increased more than five times when the foaming temperature increased to 800 °C (*maximum lead concentration at T=800°C: 0.12 mg/L*). The changes in lead concentration over temperature can be described by the following linear equation:

$$\mathbf{y = 0.002x - 1.4722}\ (\textit{Coefficient of Determination, } R^2\textit{=0.9245})$$

The leaching of barium decreases with the foaming temperature. The barium concentration (*standard limit: 100 mg/L*) decreased to 56.49 % when the foaming temperature was increased from 750 °C to 775 °C and to 77.55 % when the foaming temperature was increased to 800 °C (*maximum barium concentration at T=750°C: 9.31 mg/L*) (**Fig. A**).

The changes in barium concentration over temperature can be described by the following linear equation:

$$\mathbf{y = -\ 0.1444x + 117.06}\ (\textit{Coefficient of Determination, } R^2\textit{=0.9349})$$

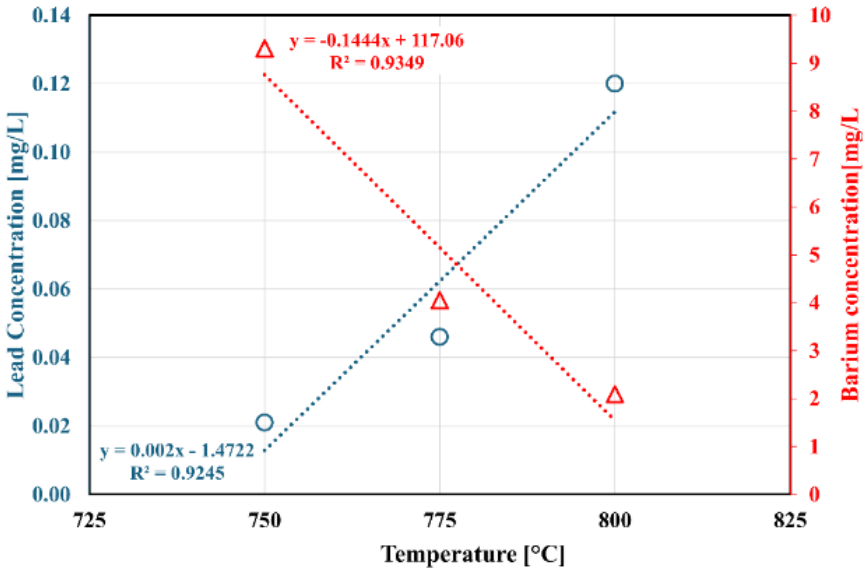


Figure A. The concentration of lead and barium contaminants from the leaching test for foam glass over the foaming temperature

Related publication: *Sarah Kareem Mohammed Al-Saudi, Robert Géber: Production of lightweight geopolymer concrete with foam glass aggregate derived from cathode-ray glass waste, Case Studies in Construction Materials, 2024.(Q1)* https://doi.org/10.1016/j.cscm.2024.e03888

Thesis 3. Prediction of physical, mechanical and thermal properties of metakaolin-based geopolymer binder

Using multilinear regression, statistical models were built to predict the bulk density, compressive strength and thermal conductivity of metakaolin-based geopolymer binders by investigating the effects of three variables, namely water glass dosage, curing temperature and liquid-to-solid ratio (**Table B**).

The metakaolin-based geopolymer binder was prepared from metakaolin (*calcinated kaolin at 750 °C for 3 hours; median particle size* (d_{50}=5.4µm)). Chemical composition (***SiO_2**: 58.3 wt.%; **Al_2O_3**:39.4 wt.%; **MgO**: 0.33 wt.%; **CaO**: 0.28 wt.%; **Na_2O**:0.06 wt.%; **K_2O**:0.26 wt.%; **Fe_2O_3**:0.47 wt.%; **MnO**:0.005 wt.%; **TiO_2**: 0.203 wt.%; **P_2O_3**: 0.013 wt.%; **S**: 0.02 wt.%).* Alkali activator solution: M_{NaOH}=10 M; water glass silicate modulus: 3.8.

Table B. Geopolymer binder variables.

Variables name	Level values
Water glass dosage (wt.%)	0; 25; 50; 75 and 100
Curing temperature (°C)	25, 60 and 75
Liquid-to-solid ratio	0.8; 0.95 and 1.1

Predictive models:

***Bulk density* (g/cm^3) = 1.478 + 0.002920 · Water glass dosage (wt.%) -0.001681 · Curing temperature (°C) - 0.286 · Liquid to solid ratio ± error (Error (%) = 4.02)**

***Compressive strength* (MPa) = 40.81 + 0.0163 · Water glass dosage (wt.%) - 0.1349 · Curing temperature (°C) - 19.49 · Liquid-to-solid ratio ± error (Error (%) =10.58)**

***Thermal conductivity* (W/m·K) = 0.981 - 0.003229 · Water glass dosage (wt.%) + 0.00070 · Curing temperature (°C) - 0.554 · Liquid-to-solid ratio ± error (Error (%) =7.47)**

Related publications:

1. A Al-Saudi Sarah Kareem Mohammed et al.: Comparative study of metakaolin-based geopolymer characteristics utilizing different dosages of water glass in the activator solution, Results in Engineering, 2023. (Q1) https://doi.org/10.1016/j.rineng.2023.101469

2. Al-Saudi Sarah Kareem Mohammed and Róbert Géber: Effect of liquid- solid ratio on metakaolin-based geopolymer binder properties, Pollack Periodica, 2024. (Q3) https://doi.org/10.1556/606.2024.01141

Thesis 4. Determination of Setting Times for Geopolymer binder and Innovation of Lightweight Metakaolin-Based Geopolymer Concrete

A. It was experimentally proved that metakaolin-based geopolymer binder with the following composition and conditions (*kaolin was calcinated at 750 °C for 3 hours; Metakaolin median particle size (d_{50}=5.4µm)). Metakaolin chemical composition (**SiO_2**: 58.3 wt.%; **Al_2O_3**:39.4 wt.%; **MgO**:0.33 wt.%; **CaO**: 0.28 wt.%; **Na_2O**:0.06 wt.%; **K_2O**:0.26 wt.%; **Fe_2O_3**:0.47 wt.%; **MnO**:0.005 wt.%; **TiO_2**: 0.203 wt.%; **P_2O_3**: 0.013 wt.%; **S**: 0.02 wt.%). Alkali activator solution: M_{NaOH}=10 M; water glass silicate modulus: 3.8. NaOH/Na_2SiO_3 ratio=1. Liquid-to-solid ratio: 1.1.)* can be set at room temperature, with an initial setting time of 288 minutes and a final setting time of 358 minutes. Both setting times meet the standard requirements for the setting time of cement (*EN 196-3:2017 standard; initial*

setting time should exceed 45 minutes; final setting time should not exceed 390 minutes). The prepared geopolymer binder has the following properties: uniaxial compressive strength: 19.12 MPa; bulk density: 1.42 g/cm³; thermal conductivity: 0.49 W/m·K.

Related publications:

1. A Al-Saudi Sarah Kareem Mohammed et al.., Comparative study of metakaolin-based geopolymer characteristics utilizing different dosages of water glass in the activator solution, Results in Engineering, 2023. (Q1) https://doi.org/10.1016/j.rineng.2023.101469

2. Al-Saudi Sarah Kareem Mohammed and Róbert Géber, Effect of liquid- solid ratio on metakaolin-based geopolymer binder properties, Pollack Periodica, 2024. (Q3) https://doi.org/10.1556/606.2024.01141

B. I have experimentally proved that it is possible to produce metakaolin-based lightweight geopolymer with foam glass aggregates derived from waste CRT glass cured at room temperature. Based on its properties (**Table C**), the newly developed lightweight geopolymer concrete meets the requirements of ASTM C 330 standard and can therefore be classified as a structural/insulating material.

Table C. The properties of the lightweight geopolymer, along with a comparison to the lightweight concrete defined by ASTM and EN standards

Properties	ASTM C 330		BS EN: 206-1	MK-based lightweight geopolymer concrete with foam glass aggregate derived from CRT waste glass
	Structural/insulating group	Insulating group		
Density (g/cm³)	0.72 – 1.44	0.24 – 0.80	0.88 – 2.00	1.17 – 1.29
Compressive strength (MPa)	3.4 – 17	0.70 – 3.40	8.00 – 80.00	8.09 – 9.11
Thermal conductivity (W/m·K)	0.45 – 1.05	0.065 – 0.22	–	0.18 – 0.283

The lightweight geopolymer was prepared from 70 vol% of metakaolin-based geopolymer and 30 vol% of foam glass aggregate. Samples were cured at room temperature for 28 days.

The metakaolin-based geopolymer was prepared with the following composition and conditions: *Metakaolin (kaolin calcinated at 750 °C for 3 hours; median particle size (d_{50}=5.4μm)). Chemical composition (**SiO_2**: 58.3 wt.%; **Al_2O_3**:39.4 wt.%; **MgO**:0.33 wt.%; **CaO**: 0.28 wt.%; **Na_2O**:0.06 wt.%; **K_2O**:0.26 wt.%; **Fe_2O_3**:0.47 wt.%; **MnO**:0.005 wt.%; **TiO_2**: 0.203 wt.%; **P_2O_3**: 0.013 wt.%; **S**: 0.02 wt.%). Alkali activator solution: M_{NaOH}=10 M; water glass silicate modulus: 3.8. NaOH/Na_2SiO_3 ratio=1. Liquid-to-solid ratio:1.1.*

Foam glass aggregate was made from 99 weight% of waste CRT glass waste (*median particle size d_{50}: 11 μm*) and 1 weight% of SiC (*$d \geq 1\mu m$*) as foaming agent. The chemical compositions of waste CRT glass: **SiO_2**: *55.9 wt.%,* **PbO**: *13.36 wt.%,* **BaO**: *10.2 wt.%,* **Na_2O**: *5.96 wt.%,* **K_2O**: *5.49 wt.%,* **SrO**: *1.51 wt.%,* **Others**: *7.85 wt.%*). Foaming temperatures: 750 °C, 775 °C and 800 °C

Related publication: *Sarah Kareem Mohammed Al-Saudi, Robert Géber: Production of lightweight geopolymer concrete with foam glass aggregate derived from cathode-ray glass waste, Case Studies in Construction Materials, 2024. (Q1) https://doi.org/10.1016/j.cscm.2024.e03888*

List of Publications

International Journal articles

1. **Al-Saudi Sarah Kareem Mohammed**, Róbert Géber, Production of lightweight geopolymer concrete with foam glass aggregate derived from cathode-ray glass waste, Case Studies in Construction Materials, (2024). https://doi.org/10.1016/j.cscm.2024.e03888. **(Q1, IF= 6.5)**
   *Number of Independent Citations: **4***
2. **Al-Saudi Sarah Kareem Mohammed**, Róbert Géber, Andrea Simon, Emese Kurovics, Alexandra Hamza, Comparative study of metakaolin-based geopolymer characteristics utilizing different dosages of water glass in the activator solution, Results in Engineering (2023). https://doi.org/10.1016/j.rineng.2023.101469 **(Q1, IF= 6)**
   *Number of Independent Citations:**24***
3. **Al-Saudi Sarah Kareem MOHAMMED, Róbert GÉBER**, Effect of liquid-solid ratio on metakaolin-based geopolymer binder properties, Pollack Periodical, (2024) **(Q3, IF=0.83)**
   *Number of Independent Citations: **4***
4. **Al-Saudi Sarah Kareem Mohammed**, Emese Kurovics, Jamal-Eldin F.M. Ibrahim, Mohammed Tihtih, Andrea Simon, Róbert Géber, Preparation of an Aluminum Titania /Mullite Composite from the Raw Materials Alumina, Titania, and Silica Fume, Revue des Composites et des Materiaux Advances, (2022). https://doi.org/10.18280/rcma.320502 **(Q3, IF=1.26).**
   *Number of Independent Citations: **3***

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1. **Al-Saudi Sarah Kareem Mohammed,** Andrea Simon, and Róbert Géber, Preparation and characterization of foam glass from soda lime silicate glass waste by using different dosages of limestone, Multidisciplinary Sciences, (2022). https://doi.org/10.35925/j.multi.2022.4.20
   *Number of Independent Citations: **4***
2. **Sarah Kareem**, Luay S.Al-Ansari, László A. Gömze, Modeling of Modulus of Elasticity of Nano-Composite Materials: Review and Evaluation, Journal of Physics: Conference Series, (2022). https://doi.org/10.1088/1742-6596/2315/1/012038 **(Q4, IF=0.56)**
   Number of Independent Citations: 7

Papers published in Almanach (ISSN 2939-7294):

1. **Al-Saudi Sarah Karem Mohammed,** Phase transformation of silica fume during sintering with alumina (2022) https://www.kerpely.uni-miskolc.hu/phd_students_almanach

2. **Al-Saudi Sarah Kareem Mohammed,** Geopolymer: An overview of polymerization on metakaolin-based geopolymer, (2023) https://www.kerpely.uni-miskolc.hu/phd_students_almanach
3. **Al-Saudi Sarah Kareem Mohammed,** Foam glass derived from waste glass: A review, (2024). *https://www.kerpely.uni-miskolc.hu/phd_students_almanach*.

Conference presentations

1. **Sarah Kareem**, Luay S.Al-Ansari, László A. Gömze, **Oral presentation**, Simulations of the Tensile Modulus of Elasticity of Various Nano-silica Particles Modified Epoxy Polymer, The 6th International Conference on Competitive Materials and Technology, Miskolc -Lillafured, Hungary, October 6th, 2021.
2. **Sarah Kareem**, László A. Gömze, **Oral presentation,** Aluminum Titanate (Al_2TiO_5) formation with small additives of oxides: Review, The Day of Hungarian Science, Miskolc, Hungary, December 11th, 2021.
3. **Sarah Kareem Mohammed**, Emese Kurovics, Jamal-Eldin F. M. Ibrahim, Mohammed Tihtih, Andrea Simon, Róbert Géber, **Poster presentation,** Development of Properties of Aluminum Titanate by Addition of Silica Fume, 25th Spring Wind Conference, Pécs, Hungary, July 5th, 2022.
4. **Sarah Karem Mohammed Al-Saudi**, Andrea Simon, Róbert Géber, **Oral presentation**, Preparation and Characterization of Foam Glass From Soda Lime Silicate Glass Waste, MultiScience - XXXV. microCAD International Multidisciplinary Scientific Conference, Miskolc University, Hungary, October 10th, 2022.
5. **Al-Saudi Sarah Kareem Mohammed**, Andrea Simon, Róbert Géber, **Oral presentation,** Investigation of the properties of foam glass produced from window glass waste and various foaming agents**,** 26th Spring Wind Conference, Miskolc, Hungary, June 5th, 2023.
6. **Al-Saudi Sarah Kareem Mohammed**, Andrea Simon, Róbert Géber, **Oral presentation**, Some properties of foam glass produced from window glass waste and various foaming agents, Glass industry professional conference, Budapest, Hungary, June 23 th,2023.
7. **Al-Saudi Sarah Kareem Mohammed**, **Oral presentation**, Study characterisation of metakaolin-based geopolymer by using different dosages of sodium silicate in the activator solution, MultiScience - XXXVI. microCAD International Multidisciplinary Scientific Conference**,** Miskolc, Hungary, December 10th, 2023.
8. **Al-Saudi Sarah Kareem Mohammed**, Robert Geber, Andrea Simon, **Oral presentation**, Produce foam glass aggregate utilising waste glass from cathode-ray tubes, 9th International Scientific Conference on Advances in Mechanical Engineering Debrecen, Hungary, September 11th, 2023.
9. **Al-Saudi Sarah Kareem Mohammed, Oral presentation,** Investigation of the Influence of Temperature on the Properties of Geopolymer Binders, The Day of Hungarian Science, Miskolc, Hungary, August 11th, 2023.
10. **Al-Saudi Sarah Kareem Mohammed**, Robert Geber, Andrea Simon, **Oral presentation,** Investigation of the effect of sintering temperature on the properties of the foam glass composition, XXVII. Spring Wind Conference, Budapest, Hungary, May 4th, 2024.

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