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Experimental evaluation of compressive, tensile strength and impact test in blast furnace slag based geopolymer concrete, under high temperature

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Abstract

Today, the use of nanoscale additives in the concrete industry with the aim of reducing the negative effects of Portland cement and improving the mechanical properties of concrete has received much attention. Also, in order to reduce the harmful environmental effects and increase the mechanical properties and durability of concrete, particles with high pozzolanic properties are used as a suitable alternative to ordinary cement in concrete. In this regard, geopolymer concrete using materials containing aluminosilicate materials with adhesive properties and filler, as an alternative to cement, has attracted the attention of researchers. Concrete resistance to high heat is of particular importance. Geopolymer concrete has a good performance against heat due to its strong structure. In the current study, slag-based geopolymer concrete was used with 0-2% polyolefin fibers and 0-8% nano-silica to improve its structure. After curing the specimens under dry conditions at a temperature of 60°C in an oven, they were subjected to Compressive strength, Tensile strength, and Drop weight hammer tests to evaluate their mechanical properties. all tests were performed at 90 days of age under ambient temperature (20 ℃) and high temperature (500 ℃). The addition of nano-silica enhanced the whole properties of the slag-based geopolymer concrete. Addition of up to 8% nanosilica to the geopolymer concrete composition at 20% temperature improved the compressive strength test results up to 21.94%, tensile strength up to 15.19% and impact energy up to 36.36%. Addition of up to 2% of polyolefin fibers to the geopolymer concrete composition improved the tensile strength up to 11.76%, the impact energy up to 8.26 times and the compressive strength drop up to 22.49%. Applying high heat to geopolymer concrete samples reduced the compressive strength up to 16%, tensile strength up to 21% and impact energy up to 72.72%. The effect of heat on the drop in results in control concrete is more than geopolymer concrete. In the following, by conducting the SEM test, a microstructure investigation was carried out on the concrete samples. In addition to their overlapping with each other, the results indicate the geopolymer concrete superiority over the regular concrete. Besides, it demonstrated the positive influence of nano-silica addition on the concert microstructure. (DOI:**https//doi.org/10.52547/JCER.4.2.12**)

Keywords **:** Geopolymer Concrete; Polyolefin Fibers; Nano silica; Blast furnace slag; Scanning electron microscope (SEM).

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1. Introduction

Cement production while consuming fossil fuels has many environmental hazards, in this regard, the production of concrete with cement alternative materials has always been the focus of researchers. Recently, the production of geopolymer concrete with high environmental properties and strength has been on the agenda of researchers.Research shows that cement plants are responsible for emitting about 5% of the total CO_2 into the Earth's atmosphere [1]. But The amount of CO_2 produced in the geopolymer process is much less than the cement production process [2]. Geopolymeris a name coined by Davidovits [3]. Geopolymer cements are a group of alkali-activated materials exhibiting superior engineering properties compared to Portland cements [4]. Geopolymer is characterized by high polymerization materials with aluminosilicate structure, which is mainly composed of three cross-linked unit dimensions, including (SiQ4 (2Al) and SiQ4 (3A) [5]. The activation of blast-furnace slag with alkaline liquids (e.g., NaOH or water glass) to produce alkali-activated slag cement has been studied during the past few decades [4]. Granulated Blast Furnace Slag (GBFS) is among the environmental materials. Using this material instead of cement can improve concrete resistance and decrease the increasing demand for its usage in concrete[6,7]. In addition to positively affecting the mechanical properties, the presence of silica particles in the geopolymer concrete accelerates the geopolymer reaction, reducing the compound alkalinity [8]. The influence of the nano-silica in improving the strength can be attributed to the following multi-stage mechanism that improves the concrete's microstructures and thus, increases the mechanical properties.

1. The rise in the pozzolanic reaction [8]. The presence of nano-silica in the geopolymer concrete accelerates the pozzolanic reaction.
2. The filling effect of nano-silica particles [9,10]. First, the distribution of nano-silica particles besides the other concrete particles results in a denser matrix. Second, the nano-silica's reaction in the geopolymerization procedure produces a larger amount of aluminosilicate gel, along with the reaction products of the main materials. The reaction by-product is likely to deposit in the structure of the existing pores. The rise in SiO_2 increases the matrix density [11]. Therefore, the filling effect of Nano-silica is improved by the particle packing, and the by-product produces a denser matrix, reducing the porosity and increasing the strength.
3. It acts as a nucleus [12,13]. In the C-S-H gel structure, nanoparticles can act as a nucleus and form strong bonds with the C-S particles of the gel. Thus, during the hydration, the products' stability increases, and the durability and mechanical products are expected to improve.

According to the investigations, nano-silica addition to the geopolymer concrete enhances its compressive strength until the Silica to Aluminum (Si/Al) ratio reaches 2% in the mixture and further silica addition decreases the compressive strength due to agglomeration and non-uniform distribution[14]. also, An improvement is reported in the respective compressive strength using nano-silica particles in the geopolymer concrete compound [15]. On the other hand, The optimum compressive strength and tensile strength coefficient were obtained by adding 6% nano-silica [16].

The presence of materials containing aluminosilicate materials in the composition of geopolymer concrete due to its pozzolanic properties, while participating in the reactivity accelerates the geopolymerization process. They fill the concrete and strengthen the bond between the aggregates and the cement paste in the interfacial transition zones (ITZ). It is done weaker. The structure of nanosilica-containing slag geopolymer concrete can be evaluated in microstructural and macrostructural dimensions. The macrostructural dimension consists of large components visible to the naked eye, which is divided into two phases of aggregate and geopolymer cement paste, but in the dimension. Microstructure Most components must be viewed with an electron microscope.According to the studies, using macroplastic fibers for concrete improvement instead of metal mesh and fibers has captured researchers' attention; the concrete-related industries widely use polyolefin-based fibers[17]. The studies have indicated that adding polyolefin fibers to the concrete beams significantly assists the resistance after being cracked due to increasing the modulus of elasticity[18]. In an investigation conducted on the effect of adding 0.5 of polyolefin fibers to the geopolymer concretes, it was observed that the compressive resistance of the samples declined by 12-15%. The samples containing fibers with 55 mm in length had undergone lower compressive strength more than those with 48 mm in length[19,20]. The addition of fibers reduces the compressive strength [21]. Comparing the concrete containing regular Portland cement with geopolymer concrete, McNulty[22] asserted that the geopolymer concretes have higher compressive strength. The comparison of the specimens with and without nano-silica showed a small number of fine cracks in the fracture, which slightly increased the impact resistance. The fibers were more effective than the nano-silica. Moreover, with the addition of polyolefin fibers to the geopolymer concrete, its failure became more flexible. This behavior was also observed for various kinds of fibers in other studies [23-25]. Geopolymer concretes resistance in encountering a significant level of heating treatment depends on its constituent chemical compounds and also the temperature and the way of curing[26]. This structure (related to the geopolymer concrete) has some merits compared to the regular concrete, e.g., it provides better resistance performance at higher temperatures[27].

The concrete resistance performance against heat is complicated. When being exposed to a high temperature, geopolymer concrete experiences a number of changes indicated based on their thermal ranges[28].

1. The removal of evaporative water at 100 °C
2. Calcium Silicate Hydrates hydration starts at 180 °C; as the temperature increases to 200 °C, the vapor pressure continuously elevates in the geopolymer structure.
3. The OH hydroxyl groups are evaporated at 500 °C. The dihydroxylation changes the Aluminosilicate structure, reducing the resistance level.
4. An intensely porous ceramic structure is formed at 800 °C.

The effect of nano-silica on improving and reducing heat resistance can be explained as a multi-step mechanism that improves the microstructure of concrete and, consequently, increases the mechanical properties of concrete.

1- Increase in pozzolanic reaction [8]: Presence of nano-silica in geopolymer concrete increases the rate of pozzolanic reaction.
2- Filer effect of Nano-silica particles [29,10]. In the first step, the distribution of the nano-silica particles besides other particles in concrete leads to the creation of a more compact matrix. Secondly, nano-silica reaction in the geopolymerization process produces a greater amount of Aluminosilicate gels and reaction products from main materials.
3- Acting as a nucleus [30,31] In the structure of C-S-H gel, nanoparticles can act as a nucleus and create strong bonds with particles of C-S-H gel.

In this laboratory research, the production of slag geopolymer concrete with optimal performance in compressive strength, tensile strength and impact hammer is introduced as an innovation. On the other hand, according to the study of others regarding the reduction of CO2 emissions by the production of geopolymer concrete, this issue is also one of the objectives of this research.

2. Experimental program

2.1 Materials

In this experimental study, the Portland cement type II with a 2.35 gr/cm^3 of specific weight according to standard En 197-1 and the Blast Furnace Slag was used in powder form with the density of 2.45 gr/cm^3 according to ASTM C989/C989M standard. The chemical properties of these materials are indicated in Table 1. The nano-silica particles made up of 99.5% SiO2 with an average diameter in the range of 15 to 25 nm were used. Crimped polyolefin fibers according to ASTM D7508/D7508M standard, 30 mm in length, were also used, whose physical properties are shown in Fig. 1. The used fine aggregates were natural clean sand with a fineness modulus of 2.95 and a density of 2.75 gr/cm^3, and the coarse aggregates were crushed gravel with a maximum size of 19 mm and a density of 2.65 gr/cm^3 according to the requirements of the ASTM-C33. In this study, the geopolymer concrete curing has been performed at 60 °C according to the geopolymer concrete standards extracted from prestigious articles in this field.

Table1

Chemical compositions of materials

Component	Slag (%)	Portland cement type (%)
SiO_2 (%)	29.2	21.3
Al_2O_3 (%)	19.4	4.7
Fe_2O_3 (%)	5.8	4.3
CaO (%)	38.6	62.7
MgO (%)	2.8	2.1
SO_3 (%)	2.6	2
K_2O (%)	0.1	0.65
Na_2O (%)	0.2	0.18
TiO_2 (%)	0.6	-
Free Cao	-	1.12
Blaine (cm^2/gr)	2200	3200
Loss on ignition (%)	0.3	1.84

Tensile Strength (N/mm^2)	>500
Length (mm)	30
Diameter (mm)	0.8
Elasticity Modulus (GPa)	>11
Bulk Density (g/cm^3)	2400

Figure. 1. Physical properties of the polyolefin fibers

2.2 Mix design

For accurate investigation, six mixture designs were considered, according to ACI 211.1-89 standard. The first sample included a regular concrete containing Portland cement where the water to cement ratio has considered to be constantly 0.45. Five other samples include geopolymer concrete with different nano-silica and polyolefin fibers. The geopolymer concrete samples are generally categorized into two groups: the first group lacks polyolefin fibers with the nano-silica amount of 0-8%. The second group contains 8% of nano-silica, where the polyolefin fibers are used in these designs in the form of 1 and 2 percent. In order to achieve the same performance in each mixture design and obtain a slump of about 20 ±100 mm, we have used normal polycarboxylate-based superplasticizers. Besides, 202.5 kg/m^3 of the alkaline solution is used in this case. The used alkaline solution is a combination of NaOH and Na_2SiO_3 with the weight ratio of 2.5, utilized with the mixture specific weight of 1483 kg/m^3 and the concentration of 12 M. The conducted studies indicate that due to the significant level of C-S-H formation when utilizing Na_2SiO_3, using a combination of NaOH and Na_2SiO_3 increases the compressive strength compared to single employment of CaOH [32]. The samples mixture design is indicated in Table 2.

Table 2

Details of the mix designs

	Mix ID	Cement	Slag	Water	Nano silica	Coarse aggregates	Fine aggregates	polyolefin fibers	Super plasticizer
		(Kg/m^3)							
1	OC-NS0PO0	450	0	202.5	0	1000	761.13	0	6.75
2	GC-NS0PO0	0	450	0	0	1000	816.10	0	6.75
3	GC-NS4PO0	0	432	0	18	1000	767.42	0	7.8
4	GC-NS8PO0	0	414	0	36	1000	718.75	0	8.3
5	GC-NS8PO1	0	432	0	36	1000	672.78	24	8.6
6	GC-NS8PO2	0	432	0	36	1000	646.28	48	9

2.3 Test methods

After fabricating the samples, for better curing and increasing the resistance properties, the samples were placed in an oven at 80 °C with a thermal rate of 4.4 °C/min for 48 h. After taking them out of the oven, the samples were kept for 90 days at an ambient temperature. After curing the samples and before performing the tests heating under standard ISO834, the samples were placed in an oven at 500 °C for 1 h. In the end, by opening the oven door, the samples reached the ambient temperature [33]. In the following, the required experiments were conducted on the concrete samples, according to the related standards. In this study, the compressive strength tests were performed on 10-cm^3 cubic specimens based on BS EN 12390. Furthermore, to determine the tensile strength of the cylindrical specimens (15 cm in diameter and 30 cm in length), the splitting tests were conducted based on ASTM C496. The concrete's resistance to dynamic loads (impacts) was measured using the drop weight hammer test according to the report by the ACI 544-2R committee. This test was conducted with repeating impacts on disks with a diameter of 15 cm and a height of 63.5 cm.

3. Results and discussion

3.1 Results of the compressive strength test

The results of the compressive strength test of concrete samples at 20°C and 500°C temperature are shown in Figure 2. Figure 3 shows the concrete sample after the compressive strength test.

The minimum and maximum compressive strengths obtained from the samples of control concrete and geopolymer concrete after exposure to 500 ° C belong to OC-NS0PO0 and GC-NS8PO0 designs of 38.89 and 75.99 MPa, respectively. GC-NS8PO0 is approximately 95% warmer than OC-NS0PO0 design. Increasing the fibers in GC-NS8PO1 and GC-NS8PO2 mixing designs, compared to GC-NS8PO0 geopolymer concrete design, increases the heat resistance of the sample. Has not been. The maximum and minimum compressive strength of the 90-day samples after heating compared to the 90-day concrete samples at room temperature belong to OC-NS0PO0 design and GC-NS8PO0 design by 37% and 8%, respectively. The percentage of reduction in compressive strength (under high temperature), the effect of the properties of the base materials (slag and nanosilica) constituting the geopolymer concrete in the samples of geopolymer concrete are evident in the results of the diagram. In this regard, the highest and lowest percentages of reduction in compressive strength of concrete samples belong to the design of OC-NS0PO0 and GC-NS8PO2 by 37 and 8%, respectively.

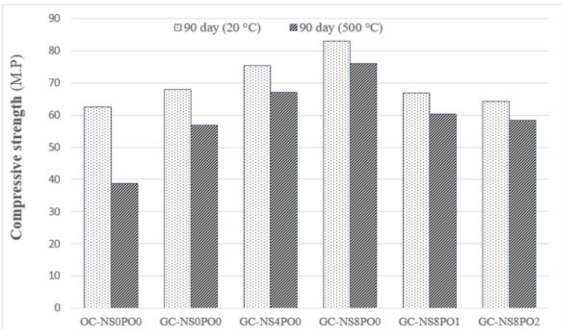

Figure. 2. The compressive strength of the specimens

Figure. 3. Concrete specimen after compressive strength test

3.2 Results of the tensile strength test

The results of the tensile strength test of concrete samples at 20°C and 500°C temperature are shown in Figure 4. Figure 5 shows the concrete sample after the tensile strength test. Based on the results, it can be seen that the minimum and maximum tensile strengths obtained from the samples of control concrete and geopolymer concrete after heating at 500 ° C belong to the OC-NS0PO0 and GC-NS8PO2 designs of 2.47 and 4.73 MPa, respectively. The strength increase is approximately 91% for the GC-NS8PO2 design compared to the OC-NS0PO0 design. The sample was exposed to heat after the samples were exposed to heat. The maximum increase in strength belongs to the GC-NS8PO2 design by 36% compared to the GC-NS0PO0 design of geopolymer concrete. The maximum and minimum tensile strength of the 90-day samples after heating compared to the 90-day concrete samples at room temperature belong to OC-NS0PO0 design and GC-NS8PO1 design by 51% and 12%, respectively. In the diagram, the highest and lowest percentages of tensile strength reduction (under high temperature) of concrete samples belong to OC-NS0PO0 and GC-NS8PO1 designs by 51 and 12%, respectively.

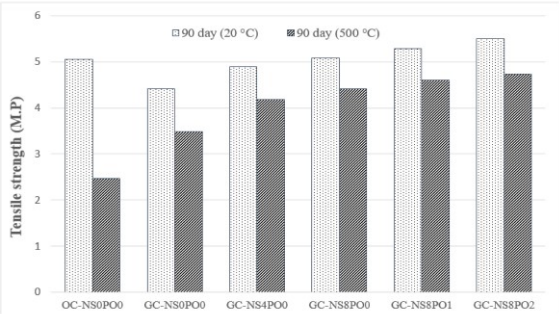

Figure. 4. The tensile strength of the specimens

Figure. 5. Concrete specimen after tensile strength test

3.3 Results of the impact test

The results of the impact test of concrete samples at 20°C and 500°C temperature are shown in Figure 6. Figure 7 shows the concrete sample after the impact test. Following the results, it is observed that with increasing heat in control concrete samples, the resistance of the samples to falling hammer blows decreases and the absorbed energy (6 times) and refractive energy (5 times) of concrete samples also decreases. Addition of 8% nanosilica and 2% polyolefin fibers to the composition of geopolymer concrete has improved the results of fracture energy and energy absorbed in the impact hammer test, this is due to the role of adhesion, filler and nucleation of silica nanoparticles in mortar Geopolymer cement and end products of geopolymerization. The amount of adsorption energy by adding 1 and 2% of fibers increases the absorbed energy by 6.2 and 9.3 times, respectively, which indicates the good ability of fibers to absorb impact energy. At 20 ° C, the minimum (223.89 J) and maximum (2829.15 J) energy absorbed in concrete samples belong to the GC-NS0PO2 and GC-NS8PO2 designs, respectively. At 500 ° C, the minimum (40.71 J) and maximum (773.44 J) absorbed energies of the OC-NS0PO0 and GC-NS0PO2 designs were obtained, respectively.

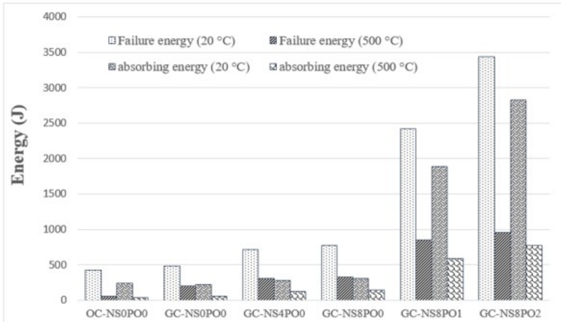

Figure. 6. The impact of the specimens

Figure. 7. Concrete specimen after impact strength test

3.4 Results of the SEM test

In this study, 10 µm scale scanning electron microscopy images at 90 days of curing age are shown on concrete samples at room temperature in Figure 8 and under high temperature in Figure 9.

In the samples under room temperature, for geopolymer concrete, by increasing the consumption of nanosilica in the designs and due to the acceleration and greater participation of these particles in the geopolymerization process, we see an increase in the production of hydrated gels in geopolymer concrete samples. In these images, the amount of white masses due to non-participation of particles in the chemical reaction process in Figure 1 (including control concrete containing Portland cement) is higher than other designs (including ferrous concrete). The increase in the volume of masses obtained from hydrated gels in the geopolymerization product is evident by increasing the amount of nanosilica in alkaline concrete designs. The reduction of porosity in the concrete microstructure has been reduced.In Portland cement, C-S-H gel consists of silicone and geopolymer groups of materials with high polymerization and Aluminosilicate structure[34]. In the sample containing nano-silica, very few fine cracks are observed, in which nano-silica acts as a filler to fill the spaces inside the hardened microstructure skeleton of the geopolymer paste and increase its compaction [14,35]. First, the nanoparticles fill the pores of the matrices, which reduces the porosity of the geopolymer nanocomposites, resulting in uniformity, less pores, and a more compact geopolymer matrix [8]. In fact, the pozzolanic reaction condenses and homogenizes the microstructures by converting C-H to C-S-H [5], thus creating more geopolymer gel and a denser matrix [36] However, further increase in NS content causes insufficient dispersion and accumulation of nano-silica particles, which slightly reduces matrix density[34]. In high temperature samples, tree structure due to water evaporation and destruction of concrete microstructure is observed. In this case, cracks and cavities in the concrete microstructure are seen more than concrete samples under room temperature. High heat on concrete has caused fundamental changes in the microstructure of concrete and Portland cement paste matrix and geopolymer, this is one of the main factors reducing the mechanical properties of concrete under high temperature, heat causes water to escape in the capillary spaces between gels Hydrate in the interfacial transition areas in concrete, water outlet also causes pores and weakens the microstructure of concrete. In general, it is believed that due to their ceramic-like properties, geopolymers have better performance in encountering fire compared to regular concretes [8,37,38]. Geopolymer concretes resistance in encountering a significant level of heating treatment depends on its constituent chemical compounds and also the temperature and the way of curing [26]. The OH hydroxyl groups are evaporated at 500 °C. The dihydroxylation changes the Aluminosilicate structure, reducing the resistance level [33]. According to the obtained results in this investigation, all designs at room temperature have "superior" quality, and all samples at 500°C have average and good quality [39].

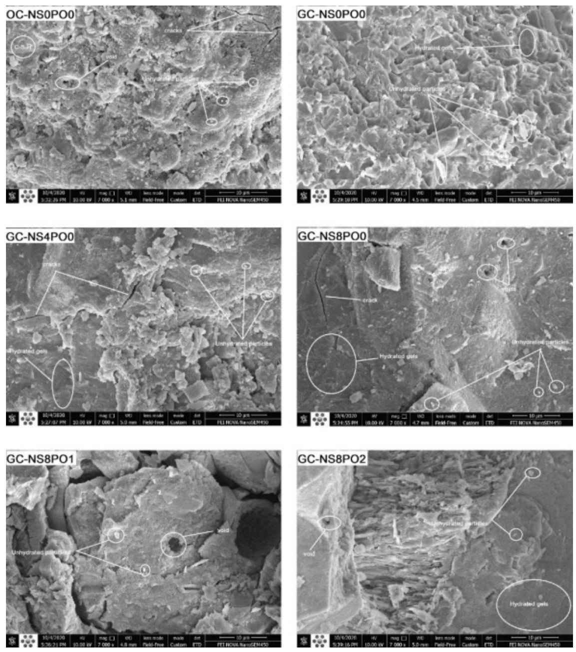

Figure. 8. Microstructure (SEM) image under room temperature

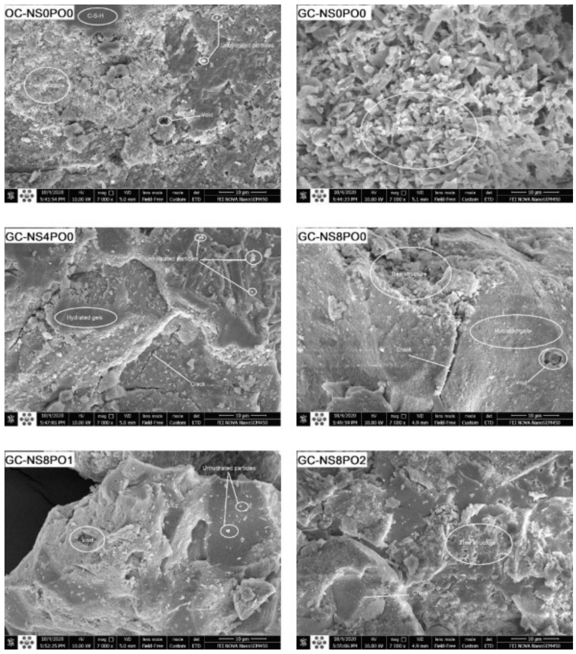

Figure. 9. Microstructure (SEM) image under high temperature

4. Conclusions

In this experimental study, compressive strength, tensile strength and impact resistance of hammer dropping in ordinary concrete and geopolymer concrete at 90 days of curing age at 20% and 500% were investigated. The results of this research are as follows.

1. At a temperature of 20%, the lowest (62.43 M.P) and the highest (82.96 M.P) compressive strength belong to design concrete 1 (including ordinary concrete) and design 4 (including geopolymer concrete containing 8% nanosilica). The lowest (4.41 M.P) and the highest (5.51 M.P) tensile strength belong to Scheme 2 (including nanosilica-free geopolymer concrete) and Scheme 6 (including geopolymer concrete containing 2% fibers). The lowest (232.89 G) and highest (2829.15 G) impact energy in the falling hammer test belongs to Figure 2 and Figure 6.
2. At a temperature of 500%, the lowest (38.89 M.P) and the highest (75.99 M.P) compressive strength belong to design concrete 1 (including ordinary concrete) and design 4 (including geopolymer concrete containing 8% nanosilica). The lowest (2.47 M.P) and the highest (4.73 M.P) tensile strength belong to design 1 and design 6 (including geopolymer concrete containing 2% fibers). The lowest (40.71 G) and highest (772.44 G) impact energy in the falling hammer test belongs to Figure 2 and Figure 6.
3. Applying high heat to geopolymer concrete samples reduced the compressive strength up to 16%, tensile strength up to 21% and impact energy up to 72.72%. The effect of heat on the drop in results in control concrete is more than geopolymer concrete.
4. The results of all tests at 20% and 500% showed the superiority of mechanical properties in geopolymer concrete compared to ordinary concrete.
5. SEM images, due to the microstructural superiority of geopolymer concrete over control concrete, covered the results of other tests in this study.

CRediT authorship contribution statement

Mohammadhossein Mansourghanaei:

Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision.

Morteza Biklaryan:

Conceptualization, Formal analysis, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Nosrati, A., Zandi, Y., Shariati, M., Khademi, K., Aliabad, M., Marto, A., & Khorami, M. (2018). Portland cement structure and its major oxides and fineness. Smart structures and systems, 22(2), 425-432.

[2] Neupane, N., Chalmers, D., & Kidd, P. (2018). High-strength geopolymer concrete properties. advantages and challenges. Advances in Materials, 7(2), 15-25.

[3] Davidovits J.Soft mineralurgy and geopolymers. Proc. 1st Int.Conf. on geopolymers. 1988. p. 19–21.

[4] Allahverdi, A. L. I., Ebrahim Najafi Kani, and Mahshad Yazdanipour. "Effects of blast-furnace slag on natural pozzolan-based geopolymer cement." Ceramics-Silikáty 55.1 (2011): 68-78.

[5] Du, H., S. Du, and X. Liu, Durability performances of concrete with nano-silica. Construction and building materials, 2014. 73: p. 705-712.

[6] Siddique, R. and D. Kaur, Properties of concrete containing ground granulated blast furnace slag (GGBFS) at elevated temperatures. Journal of Advanced Research, 2012. 3(1): p. 45-51.

[7] Yüksel, İ., R. Siddique, and Ö. Özkan, Influence of high temperature on the properties of concretes made with industrial by-products as fine aggregate replacement. Construction and building materials, 2011. 25(2): p. 967-972.

8. Assaedi, H., et al., Influence of nano silica particles on durability of flax fabric reinforced geopolymer composites. Materials, 2019. 12(9): p. 1459.

[9] Beigi, M.H., et al., An experimental survey on combined effects of fibers and nanosilica on the mechanical, rheological, and durability properties of self-compacting concrete. Materials & Design, 2013. 50: p. 1019-1029

[10] Deb, P.S., P.K. Sarker, and S. Barbhuiya, Sorptivity and acid resistance of ambient-cured geopolymer mortars containing nano-silica. Cement and Concrete Composites, 2016. 72: p. 235-245.

[11] Law, D.W., et al., Long term durability properties of class F fly ash geopolymer concrete. Materials and Structures, 2015. 48(3): p. 721-731.

[12] Bahadori, H. and P. Hosseini, Reduction of cement consumption by the aid of silica nano-particles (investigation on concrete properties). Journal of Civil Engineering and Management, 2012. 18(3): p. 416-425.

[13] Bosiljkov, V.B., SCC mixes with poorly graded aggregate and high volume of limestone filler. Cement and Concrete Research, 2003. 33(9): p. 1279-1286.

[14] Deb, P.S., P.K. Sarker, and S. Barbhuiya, Effects of nano-silica on the strength development of geopolymer cured at room temperature. Construction and building materials, 2015. 101: p. 675-683.

[15] Adak, D., M. Sarkar, and S. Mandal, Structural performance of nano-silica modified fly-ash based geopolymer concrete. Construction and Building Materials, 2017. 135: p. 430-439.

[16] Adak, D., M. Sarkar, and S. Mandal, Effect of nano-silica on strength and durability of fly ash based geopolymer mortar. Construction and Building Materials, 2014. 70: p. 453-459.

[17] Alberti, M.G., A. Enfedaque, and J.C. Gálvez, Improving the reinforcement of polyolefin fiber reinforced concrete for infrastructure applications. Fibers, 2015. 3(4): p. 504-522.

[18] Chellapandian, M., A. Mani, and S.S. Prakash, Effect of macro-synthetic structural fibers on the flexural behavior of concrete beams reinforced with different ratios of GFRP bars. Composite Structures, 2020. 254: p. 112790.

[19] Noushini, A., A. Castel, and R.I. Gilbert, Creep and shrinkage of synthetic fibre-reinforced geopolymer concrete. Magazine of Concrete Research, 2019. 71(20): p. 1070-1082.

[20] Noushini, A., et al., Mechanical and flexural performance of synthetic fibre reinforced geopolymer concrete. Construction and Building Materials, 2018. 186: p. 454-475.

[21] Galan, A. Estimate of concrete strength by ultrasonic pulse velocity and damping constant. in Journal Proceedings. 1967.

[22] McNulty, E., Geopolymers: an environmental alternative to carbon dioxide producing ordinary Portland cement. Department of Chemistry, The Catholic University of America, 2009.

[23] Alberti, M.G., A. Enfedaque, and J.C. Gálvez, Improving the reinforcement of polyolefin fiber reinforced concrete for infrastructure applications. Fibers, 2015. 3(4): p. 504-522.

[24] Olivito, R. and F. Zuccarello, An experimental study on the tensile strength of steel fiber reinforced concrete. Composites Part B: Engineering, 2010. 41(3): p. 246-255.

[25] Islam, A., et al., Influence of steel fibers on the mechanical properties and impact resistance of lightweight geopolymer concrete. Construction and Building Materials, 2017. 152: p. 964-977.

[26] Türkmen, İ., et al. Fire resistance of geopolymer concrete produced from Ferrochrome slag by alkali

activation method. in 2013 International Conference on Renewable Energy Research and Applications (ICRERA). 2013. IEEE.

[27] Aslani, F., Thermal performance modeling of geopolymer concrete. Journal of Materials in Civil Engineering, 2016. 28(1): p. 04015062.

[28] Bakhtiyari, S., et al., Self-compacting concrete containing different powders at elevated temperatures–Mechanical properties and changes in the phase composition of the paste. Thermochimica acta, 2011. 514(1-2): p. 74-81.

[29] Beigi, M.H., et al., An experimental survey on combined effects of fibers and nanosilica on the mechanical, rheological, and durability properties of self-compacting concrete. Materials & Design, 2013. 50: p. 1019-1029.

[30] Bahadori, H. and P. Hosseini, Reduction of cement consumption by the aid of silica nano-particles (investigation on concrete properties). Journal of Civil Engineering and Management, 2012. 18(3): p. 416-425.

[31] Bosiljkov, V.B., SCC mixes with poorly graded aggregate and high volume of limestone filler. Cement and Concrete Research, 2003. 33(9): p. 1279-1286.

[32] Pilehvar, S., et al., *Physical and mechanical properties of fly ash and slag geopolymer concrete containing different types of micro-encapsulated phase change materials.* Construction and Building Materials, 2018. **173**: p. 28-39.

[33] Kong, D.L. and J.G. Sanjayan, *Effect of elevated temperatures on geopolymer paste, mortar and concrete.* Cement and concrete research, 2010. **40**(2): p. 334-339.

[34] Supit, S.W.M. and F.U.A. Shaikh, Durability properties of high volume fly ash concrete containing nano-silica. Materials and structures, 2015. 48(8): p. 2431-2445.

[35] Shih, J.-Y., T.-P. Chang, and T.-C. Hsiao, Effect of nanosilica on characterization of Portland cement composite. Materials Science and Engineering: A, 2006. 424(1-2): p. 266-274.

[36] Phoo-ngernkham, T., et al., The effect of adding nano-SiO_2 and nano-Al2O3 on properties of high calcium fly ash geopolymer cured at ambient temperature. Materials & Design, 2014. 55: p. 58-65.

[37] Ryu, G.S., et al., The mechanical properties of fly ash-based geopolymer concrete with alkaline activators. Construction and Building Materials, 2013. 47: p. 409-418.

[38] Mehdipour, S., et al., Mechanical properties, durability and environmental evaluation of rubberized concrete incorporating steel fiber and metakaolin at elevated temperatures. Journal of Cleaner Production, 2020. 254: p. 120126.

[39] Whitehurst, E.A. Soniscope tests concrete structures. in Journal Proceedings. 1951.