J-Researchers

JOURNAL OF CIVIL ENGINEERING RESEARCHERS

Experimental study of compressive strength, permeability and impact testing in geopolymer concrete based on Blast furnace slag

Mohammadhossein Mansourghanaei[a*], Morteza Biklaryan[b]

[a,b]*Department of Civil Engineering, Chalous Branch, Islamic Azad University, Chalous, Iran*

Article History: Received date 12 July 2022; revised date 9 September 2022; 23 September 2022

Abstract

Cement production has always been associated with environmental challenges due to carbon dioxide emissions. On the other hand, cement production is an energy-intensive process and leads to the consumption of abundant fossil fuels. In order to solve this problem, the production of geopolymer concrete is on the agenda. The researchers decided to reduce the negative effects of cement production and have superior properties than ordinary concrete. 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 compress strength, tensile strength and Drop weight hammer tests to evaluate their mechanical properties, as well as Permeability test to assess their durability. tests were performed at 7 and 90 days of age at ambient temperature (20℃). The addition of nano-silica enhanced the whole properties of the slag-based geopolymer concrete. Increasing the curing age improved the results of all tests. The results of all tests in geopolymer concrete showed the superiority of the results over conventional concrete. At the 28-day curing age, the addition of up to 8% nanosilica to the geopolymer concrete composition improved the compressive strength test results by 19.01%, water permeability by up to 35% and impact strength by up to 36.36%. Addition of up to 2% of polyolefin fibers in the composition of geopolymer concrete resulted in a 28.95% decrease in compressive strength but a 20% improvement in water permeability and an 8.26-fold increase in impact strength. 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.4.3.31**)

Keywords **:** Geopolymer Concrete; Polyolefin Fibers; Nano Silica; Blast Furnace Slag; Scanning Electron Microscope (SEM).

* Corresponding author. Tel.: +98-912-171-2070 ; E-mail: Mhm.ghanaei@iauc.ac.ir

1. Introduction

Today, the reduction of mineral and fossil resources and the need for concrete with high mechanical properties and durability, led scientists to think about finding a suitable material to replace cement in concrete. On the other hand, annual cement production emits high volumes of toxic CO_2 gas into the atmosphere. Research shows that cement plants are responsible for emitting about 5% of the total CO_2 into the Earth's atmosphere [1]. In order to solve these problems, the replacement of cement with pozzolanic materials containing abundant aluminosilicate materials that can create good adhesion in concrete was considered, the final product of this process is called geopolymer concrete.Geopolymeris a name coined by Davidovits [2]. The amount of CO_2 produced in the geopolymer process is much less than the cement production process [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 SiQ_4(2Al) and SiQ_4(3A) [5]. In Portland cement, C-S-H gel consists of silicone and geopolymer groups of materials with high polymerization and Aluminosilicate structure [6]. Replacing cement with these pozzolans reduces environmental pollution, improves the mechanical properties of concrete, and lowers the considerable need for cement [7,8]. In alkaline concrete, instead of cement, geopolymeric materials containing abundant aluminosilicate materials and alkaline solutions are used, which combine together in a chemical process called geopolymerization to produce hydrated gels with high adhesion and filling properties. These gels play an important role in improving the mechanical properties and durability of concrete by affecting the microstructure of concrete. The structure of 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 cement paste, but in the microstructural dimension most components must be Observe electron microscope (SEM) devices. In the microstructure dimension (in the geopolymerization process), C-S-H crystals and the second generation of crystals formed from calcium hydroxide ($Ca(OH)_2$) and ettringite gel (C-A-S-H) begin to fill in the gaps in the ettringite and calcium hydroxide network (called Portelite).) And with this operation, the density, hardness and strength of the interfacial transfer area (ITZ) of concrete increases.Comparing the concrete containing regular Portland cement with geopolymer concrete, McNulty [9] asserted that the geopolymer concretes have higher compressive strength. 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[10,11]. Ground granulated blast-furnace slag (GGBFS) has latent hydraulic properties that could be activated using suitable activators [12]. 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]. 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 [13]. 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 [13]. The presence of nano-silica in the geopolymer concrete accelerates the pozzolanic reaction.

2. The filling effect of nano-silica particles [14,15]. 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 [16]. 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 [17,18]. 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.

Improved compressive strength have been reported with the use of nano-silica in geopolymer concrete [19]. nanoparticles prevented the reduction in the geopolymer strength [13]. And 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 [20,21]. The nano-silica addition to the geopolymer concrete increases the geopolymerization reaction. In this case, more amorphous geopolymer gel is created in the matrices. This issue, in turn, indicates that the nano-silica particles prevent the resistance decline of geopolymer concrete[13]. The simultaneous evaluation of nano-silica and steel fibers in geopolymer concrete has indicated a good relationship between them [22,23]. Preventing the connection of pores and bonding the flow channels in the concrete, the polyolefin fibers strengthen it and avoid its spalling [24]. 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[25]. In an investigation on the effect of polyolefin fibers with different diameters and lengths in geopolymer concretes, it was revealed that the proper use of fibers increases the compressive strength, and impact energy, and reduces water absorption. Besides, adding fibers decreases the compressive strength[26]. The addition of fibers reduces the compressive strength [27]. The reason for the reduction in the compressive strength of specimens containing polyolefin fibers can be the micro internal defects in the geopolymer matrix caused by the additional fibers [28]. But in an investigation on the effect of polyolefin fibers with different diameters and lengths in geopolymer concretes, it was revealed that the proper use of fibers increases the compressive strength and impact energy, and reduces water absorption. Besides, adding fibers decreases the compressive strength[26]. the effectiveness of fibers when facing impact loads is extremely more than nano-silica in concrete samples. Besides, by the addition of polyolefin fibers to geopolymer concrete, concrete has become more flexible. This behavior is also observed by other fibers in the investigations conducted by other researchers[25,29,30].

In this laboratory study, increasing the mechanical properties and durability of slag geopolymer concrete containing nanosilica and polyolefin fibers is one of the innovative goals. On the other hand, according to the research of others, helping the healthy environment by reducing CO_2 emissions from conventional cement production, is another goal in this research.

2. Experimental program

2.1 Materials

In this experimental study, the Portland cement type II with a 2.35 g/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 g/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% SiO_2 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 g/cm^3, and the coarse aggregates were crushed gravel with a maximum size of 19 mm and a density of 2.65 g/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 II (%)
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/g)	2200	3200
LOI (%)	0.3	1.84

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

Fig. 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 [31]. The samples mixture design is indicated in Table 2.

Table 2. Details of the mix designs

	Mix ID	Cement	Slag	Water	Alkaline solution	Nano silica	Coarse aggregates	Fine aggregates	polyolefin fibers	Super plasticizer
		(Kg/m^3)								
1	OC	450	0	202.5	0	0	1000	761	0	6.75
2	GPCNS0PO0	0	450	0	202.5	0	1000	816	0	6.75
3	GPCNS4PO0	0	432	0	202.5	18	1000	767	0	7.8
4	GPCNS8PO0	0	414	0	202.5	36	1000	718	0	8.3
5	GPCNS8PO1	0	432	0	202.5	36	1000	672	24	8.6
6	GPCNS8PO2	0	432	0	202.5	36	1000	646	48	9

2.3 Test Metods

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. In this study, the compressive strength tests were performed on 10-cm^3 cubic specimens based on BS EN 12390. 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. According to EN 12390-8, the water permeability tests were performed on 150×150×150-mm^3 cubic specimens with a water pressure of 50±500 k.Pa on a circular area with a diameter of 75 mm on one of the surfaces for 72 hours. The permeability coefficient is calculated as the following [32]:

$$K = \frac{e^2 v}{2ht}(m/s) \quad \text{Eq. 1}$$

where e is the penetration depth (m), v is the volume fraction of concrete, h is the hydraulic length of concrete, and t is the duration it is under water pressure.

3. Results and discussion

3.1 Results of the compressive strength test

The results of the compressive strength test are shown in Figure 2. Figure 3 shows a concrete sample undergoing compressive strength test. Following these results, it is observed that increasing the curing age in the samples has improved the results up to 48.89% in ordinary concrete and 21.78% in geopolymer concrete. In each processing period, the maximum amount of results is related to the GC-NS8PO0 scheme. Addition of nanosilica to geopolymer concrete designs has improved the results. At the 90-day curing age (as the best performance), the addition of 8% nanosilica improved the compressive strength by 21.94%. Nanosilica particles due to their high filling and adhesion properties have been able to help produce a large volume of hydrated gels in the composition of concrete, these gels in combination with other materials and by creating a proper bond have increased the strength of concrete. The minimum compressive strength obtained at the age of 90 days at 62.43 M.Pa belongs to the OC-NS0PO0 design and the maximum at 82.96 M.Pa belongs to the GP-NS8PO0 design. Addition of polyolefin fibers to the composition of geopolymer concrete has reduced the compressive strength. In this regard, at the curing age of 90 days, adding 2% of fibers to concrete has caused a 22.49% decrease in compressive strength. The reason for the reduction in the compressive strength of specimens containing polyolefin fibers can be the micro internal defects in the geopolymer matrix caused by the additional fibers [28].

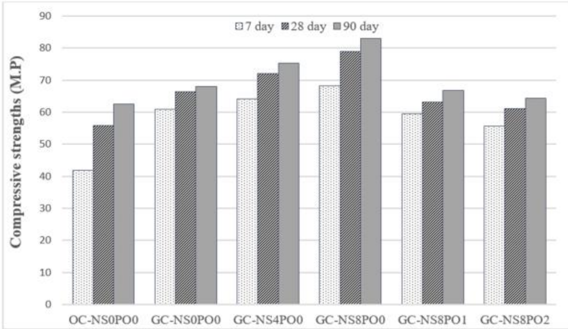

Fig. 2. The compressive strengths of the specimens


Fig. 3. Concrete sample in compressive strength test

3.2 Results of the impact test

The required fracture energy and adsorbed energy in concrete specimens are shown in Figure 4 based on the results of the hammer impact test at a working age of 90 days at a temperature of 20%. The lowest (427.43 J) and highest (3439.76 J) energy required for failure of concrete samples belong to OC-NS0PO0 design and GC-NS8PO2 design, which has a difference of 7.04 times. Addition of 8% nanosilica to 58.33% and addition of 2% polyolefin fibers to the geopolymer concrete design up to 3.44 times improved the fracture energy. The lowest (223.89 J) and highest (2829.15 J) amount of energy absorbed in concrete samples belong to the design, which has a difference of 11.63 times. Addition of polyolefin fibers to the geopolymer concrete design had a significant effect on improving the impact test results. The fibers prevent them from spreading by bridging the cracks. Preventing the connection of pores and bonding the flow channels in the concrete, the polyolefin fibers strengthen it and avoid its spalling [24]. Figure 5 shows the concrete sample after the impact strength test.

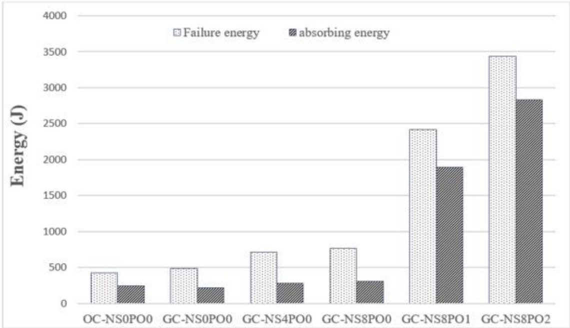

Fig. 4. The impact of the specimens

Fig. 5. Pattern of fracture of specimens in impact test

3.3 Results of the water permeability test

The results of water permeability test in concrete samples at 7, 28 and 90 days of curing age are shown in Figure 6. Figure 7 shows a concrete sample measuring the amount of water absorption in a concrete sample. Increasing the curing age has reduced the water penetration coefficient by 36.1% in ordinary concrete and up to 84.35% in geopolymer concrete samples. At the processing age of 90 days (as the best performance), the addition of 8% nanosilica and 2% polyolefin fibers to the geopolymer concrete design has improved the water permeability results by 43.99% and 55.41%, respectively. In this way 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 [13]. Also Preventing the connection of pores and bonding the flow channels in the concrete, the polyolefin fibers strengthen it and avoid its spalling [24].

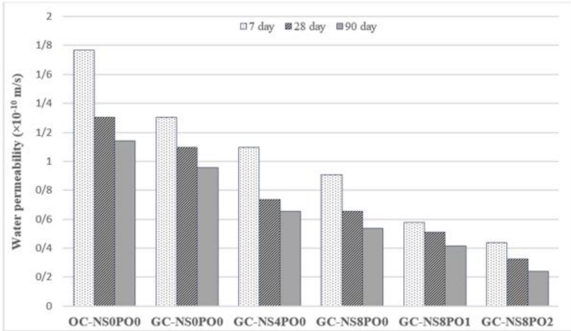

Fig. 6. The water permeability of the specimens

Fig. 7. The amount of water absorption in the specimens

3.4 Results of the SEM test

In this study, scanning electron microscope images at a scale of 500 nm were taken on concrete samples and shown in Figure 8. The volume of hydrated gels in the sample of ordinary concrete is less than that of geopolymer concrete. Cracks, cavities and unreacted particles are observed in all designs, but their amount in ordinary concrete is more than geopolymer concrete. In samples of geopolymer concrete containing nanosilica, the concrete microstructure has a better density and the volume of cavities and unreacted particles is reduced. Because 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 [13]. 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 [33] However, further increase in NS content causes insufficient dispersion and accumulation of nano-silica particles, which slightly reduces matrix density [6]. The nano-silica addition to the geopolymer concrete increases the geopolymerization reaction. In this case, more amorphous geopolymer gel is created in the matrices. This issue, in turn, indicates that the nano-silica particles prevent the resistance decline of geopolymer concrete[13]. The presence of some microcracks in the structure of geopolymer concrete is due to heat treatment below 60℃. But 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 [20,21].

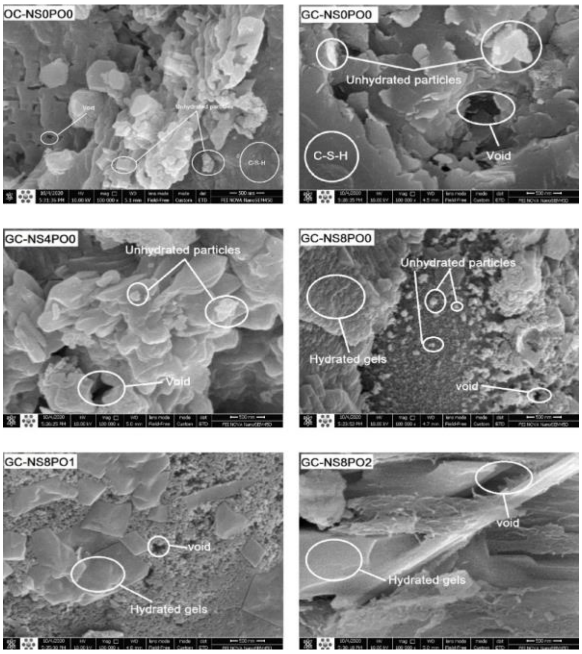

Fig. 8. Microstructure (SEM) image under room temperature

4. Conclusions

In this experimental study, compressive strength, impact strength and permeability of slag geopolymer concrete at 7 and 28 days of processing age were investigated. SEM test was performed on concrete samples at 90 days of processing age. The results of this research are as follows.

1. Increasing the curing age improved the results. In this regard, at 28 days of processing age, the lowest (55.78 M.Pa) and maximum (78.91 M.Pa) compressive strength belonged to design 1 (ordinary concrete) and design 4 (geopolymer concrete containing 8% nanosilica). At impact strength, the lowest (244.24 j) and highest (2829.15 j) impact energy obtained from Scheme 1 and Scheme 6 (geopolymer concrete containing 8% nanosilica and 2% fibers) were obtained. In the water permeability test in concrete, the best (16 mm) and weakest (32 mm) performance belonged to Figure 6 and Figure 1.
2. At 28 days of curing age, adding up to 8% nanosilica to the geopolymer concrete composition improved the compressive strength test results by 19.01%, water permeability by up to 40.29% and impact strength by up to 36.36%.
3. Addition of up to 2% of polyolefin fibers in the composition of geopolymer concrete at the age of 28 days of curing resulted in a 28.95% decrease in compressive strength but a 20% improvement in water permeability and 50.16% in impact strength.
4. The results of all tests showed the superiority of mechanical properties and durability 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.

Acknowledgments

This reseach was done with the support of Islamic Azad University, Chalous Branch.

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. Davidovits J.Soft mineralurgy and geopolymers. Proc. 1st Int.Conf. on geopolymers. 1988. p. 19–21.[13] Davidovits J. Geopolymers: man made rocks, geosynthesisand the resulting development of very early high strengthcements. J Mater Educ

1994;16:91–139.[14] Wang H, Li Haihong, Yan F. Synthesis and mechanicalproperties of metakaolinite – based geopolymer. ColloidsSurf A 2005;268:1–6.

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

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. 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.

7. 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.

8. 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.

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

10. 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.

11. 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.

12. Davidovits J.: US Patent No. 4509985, 1985.

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

14. 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.

15. 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.

16. 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.

17. 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.

18. 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.

19. 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.

20. 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.

21. 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.

22. Gülşan, M.E., et al., Development of fly ash/slag based self-compacting geopolymer concrete using nano-silica and steel fiber. Construction and Building Materials, 2019. 211: p. 271-283.

23. Their, J.M. and M. Özakça, Developing geopolymer concrete by using cold-bonded fly ash aggregate, nano-silica, and steel fiber. Construction and Building Materials, 2018. 180: p. 12-22.

24. Yousefvand, M., Y. Sharifi, and S. Yousefvand, An Analysis of the Shear Strength and Rupture Modulus of Polyolefin-Fiber Reinforced Concrete at Different Temperatures. Journal of civil Engineering and Materials Application, 2019. 3(4): p. 238-254.

25. 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.

26. Rashad, A.M., The effect of polypropylene, polyvinyl-alcohol, carbon and glass fibres on geopolymers properties. Materials Science and Technology, 2019. 35(2): p. 127-146.

27. Rashad, A.M., The effect of polypropylene, polyvinyl-alcohol, carbon and glass fibres on geopolymers properties. Materials Science and Technology, 2019. 35(2): p. 127-146.

28. Wang, K., S.P. Shah, and P. Phuaksuk, Plastic shrinkage cracking in concrete materials-Influence of fly ash and fibers. ACI Materials Journal, 2002. 99(5): p. 512-513.

29. 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.

30. 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.

31. 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.

32. Ahmad, S.I. and M.A. Hossain, *Water permeability characteristics of normal strength concrete made from crushed clay bricks as coarse aggregate.* Advances in Materials Science and Engineering, 2017. **2017**.

33. Phoo-ngernkham, T., et al., The effect of adding nano-SiO2 and nano-Al2O3 on properties of high calcium fly ash geopolymer cured at ambient temperature. Materials & Design, 2014. 55: p. 58-65.