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Research Paper

Experimental Study of Mechanical Properties of Slag Geopolymer Concrete under High Temperature, Used in Road Pavement

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Abstract

Providing the mechanical properties of concrete used in road paving is of great importance. In the current study, Granulated Blast Furnace Slag (GBFS) based geopolymer concrete (GPC) was used with 0-2% polyolefin fibers (POFs) and 0-8% Nano Silica (NS) to improve its structure. After curing the specimens under dry conditions at a temperature of 60 °C in an oven, they were subjected to Tensile Strength, Modulus of Elasticity and Ultrasonic Pulse Velocity (UPV) 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 NS enhanced the whole properties of the GBFS-based GPC. Addition of up to 8% NS to the GPC composition at 20% temperature improved the modulus of elasticity test results by 13.42%, tensile strength by 15.19% and UPV by 11.58%. Addition of up to 2% of POFs to the composition of GPC improved the tensile strength up to 11.76%, modulus of elasticity 07.05% and UPV drop up to 12.02%. Applying high heat to GPC samples reduced the modulus of elasticity by up to 42%, tensile strength by up to 21% and UPV by up to 46%. The effect of heat on the drop in results in control concrete is more than GPC. In the following, by conducting the Scanning Electron Microscope (SEM) analysis, a microstructure investigation was carried out on the concrete samples. In addition to their overlapping with each other, the results indicate the GPC superiority over the regular concrete.

Keywords: Geopolymer Concrete (GPC), Polyolefin Fibers (POFs), Nano Silica (NS), Granulated Blast Furnace Slag (GBFS), Scanning Electron Microscope (SEM)

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1. Introduction

The road transportation industry has progressed a lot in the last few decades, in this regard, ensuring the quality of passing roads is the responsibility of civil engineering scientists. Concrete is one of the most widely used materials in paving roads with high traffic volume. Of course, the quality of the concrete road pavement depends on the quality of the road infrastructure [Sazonova et al. 2022; Xu et al. Aggregates are one of the main components of pavement concrete. Therefore, the properties of aggregate used have a great impact on the properties of road pavement concrete [Pradhan et al. 2022; Vega et al. 2022; Tiyasangthong et al. 2022]. On the other hand, adding fibers to the road pavement concrete composition leads to improvement of the strength of this type of concrete [Kori, K., & Goliya. 2022]. Thermal stress and cold stress are the most influential factors in road paving [Pszczola et al. 2022; Wei et al. 2022; Jitsangiam et al. 2022]. High Temperature can lead to destruction of road pavement. Researchers are incorporating waste and industrial by-products into concrete for road development and maintenance [Loureiro et al. 2022]. In this way, while reducing costs and improving concrete performance, they can produce nature-friendly road construction concrete. In the last three decades, the gigantic demand for sustainable and environmentally friendly concrete with reduced environmental footprints has resulted in the development of low carbon concretes such as GPC [Jindal et al. 2022]. GPC is a perfect alternative to conventional cement concrete [Verma[1] et al. 2022]. Which has superior mechanical properties compared to ordinary Portland cement concrete (OPCC) [Mansourghanaei[1] et al. 2022; Mansourghanaei[2] et al. 2022; Mansourghanaei[3] et al. 2022]. In the process of substituting ordinary Portland cement (OPC) concrete production, the development of GPC is considered as the major breakthrough [Li et al. 2022]. Geopolymers are cementitious materials known for their environmental benefits and comparable characteristics to conventional Portland cement [Lyu et al. 2022]. GPC is a new material in the construction industry, with different chemical compositions and reactions involved in a binding material. The pozzolanic materials (industrial waste like fly ash, GBFS), which contain high silica and alumina, work as binding materials in the mix. GPC is economical, low energy consumption, thermally stable, easily workable, eco-friendly, cementless, and durable [Verma[2] et al. 2022].

GPC is produced from the geopolymerization process, in which molecules known as oligomers integrate to form geopolymer networks with covalent bonding [Wong. 2022].

Production and utilization of cement severely affect the environment due to the emission of various gases. The application of GPC plays a vital role in reducing this flaw [Ahmad et al. 2022]. To reduce CO_2 emissions by 55% by 2030, applying sustainable and energy-efficient materials like GPC containing Phase change materials for infrastructure development is necessary [Asadi et al. 2022]. GPCs have lower CO_2 emissions than conventional concrete and Portland cement [Jindal et al. 2022; Asadi et al. 2022; Memiş and Bılal. 2022; Sathish Kumar et al. 2022; Kanagaraj et al. 2022]. GPC is one of the innovative eco-friendly materials that has gained the attention of many researchers in the sustainable development of the construction industry [Sathish Kumar et al. 2022]. Geopolymers are environmentally friendly materials made from industrial solid waste with high silicon and aluminum contents [Niu et al. 2022]. GPC is a high-performance concrete [da Silva et al. 2022]. Geopolymer or alkali-activated binders are emerging as a potential green sustainable alternative for OPC [Albidah et al. 2022]. GPC has superior mechanical and durability properties compared to OPCC [Srividya et al. 2022]. SEM images exhibited that the geopolymer matrix contained more dispersed small-sized pores which indicate a higher compressive strength absolutely than other experimental mixes [Amin et al. 2022]. The parameters that are identified to influence the strength gain process of GPC includes type of binder, binder to Active alkali solution (AAS) ratio, alkali activators ratio, curing time, curing temperature, concentration of alkali activators, and Si/Al ratio in the binder material and activators [Upadhyay et al. 2022]. The AAS to binder ratio, molarity, NaOH content, curing temperature, and ages were those parameters that have significant influences on the Compression strength of GPC incorporated with NS [Ahmed et al. 2022]. Increasing the molarity and Alkaline to Binder ratios results in the strength development of GPC up to a specific limit [Shilar et al. 2022]. Metakaolin, fly ash, and mostly GBFS are traditionally used in the production of geopolymer [Memiş and Bılal. 2022]. In GPC, GBFS were used as binder material, along with sodium hydroxide and sodium silicate solutions as activator solutions [Kanagaraj et al. 2022]. GPC has no cement and instead of cement, the other two materials, the first of which is based on aluminous silicate materials and is known as a precursor in the production process of GPC, and the second consumable that has the role of chemical reactivity is AAS. Among the aluminate silicate materials used in the preparation of GPC, we can mention pozzolans, the most widely used of which are fly ash and GBFS of the composing furnace. The use of GBFS and fly ash has been reported in many research works [Phair and Van Deventer. 2002; Swanepoel and Strydom. 2002]. AASs include sodium hydroxide and sodium silicate. The activation of GBFS with alkaline liquids (e.g., NaOH or water glass) to produce alkali-activated GBFS cement has been studied during the past few decades [Allahverdi et al. 2011]. The presence of materials containing aluminosilicate materials in the composition of GPC, due to their pozzolanic properties, can accelerate the geopolymerization process while participating in the reactivity. Aluminum is hydrated sodium, these gels, while having a high density and density in themselves, can well fill the cavities and pores in the mortar and strengthen the connection between the aggregates and cement paste in the interfacial transition areas, and thus lead to produce dense and strong GPC, this process is done in ordinary concrete containing Portland cement due to the production of a smaller amount of hydrated gel called hydrated calcium silicate (CSH) in weaker amounts. Replacing cement with these pozzolans reduces environmental pollution, improves the mechanical properties of concrete, and lowers the considerable need for cement [Ryu et al. 2013; Mehdipour. 2020]. The presence of nanomaterials, which enhances the rate of polymerization, leads to better performance of the geopolymer [Shilar et al. 2022]. Recent efforts have been made to incorporate various nanomaterials, most notably NS, into GPC to improve the composite's properties [Ahmed[1] et al. 2022]. the addition of nanoparticles has a promising future for developing high-performance geopolymer composites that the construction industry can efficiently implement due to significant improvements in strength, durability, microstructure by providing additional C–S–H, N-A-S-H, and C-A-S-H gels as well as filling nano-pores in the geopolymer matrix [Ahmed[2] et al. 2022]. The NS addition to the GPC increases the geopolymerization reaction. In this case, more amorphous geopolymer gel is created in the matrices. This issue, in turn, indicates that the NS particles prevent the resistance decline of GPC [Assaedi et al. 2019]. NS is amorphous and the increase in amorphous material in nanocomposite samples is usually attributed to the additional NS loaded in the pastes at the nan fill capacity [Phoo-ngernkham et al. 2014; Nazari et al. 2015]. The optimum tensile strength coefficient was obtained by adding 6% NS [Adak et al. 2014]. Improved elastic modulus and UPV have been reported with the use of NS in GPC [Ekinci et al. 2019]. In the sample containing NS, very few fine cracks are observed, in which NS acts as a filler to fill the spaces inside the hardened microstructure skeleton of the geopolymer paste and increase its compaction [Deb et al. 2015; Shih et al. 2006]. The simultaneous evaluation of NS and steel fibers in GPC has indicated a good relationship between them [Gülşan et al. 2019; there and Özakça. 2018]. The impact of fiber on the long-term behavior of GPC have been highlighted [Li et al. 2022]. The addition of different fibers also has essential potential for increasing the performances of geopolymer composites [Kuranl et al. 2022]. In an investigation on the effect of POFs with different diameters and lengths in GPCs, it was revealed that the proper use of fibers increases the modulus of elasticity . Besides, adding fibers decreases the compressive strength [Rashad, 2019]. It is believed that due to their ceramic-like properties, geopolymers have better performance in encountering fire compared to regular concretes [Mehdipour et al. 2020; Ryu et al. 2013; Phoo-ngernkham. 2014]. GPCs resistance in encountering a significant level of heating treatment depends on its constituent chemical compounds and also the temperature and the way of curing [Türkmen et al. 2013]. Some researchers have reported that this reduction in resistance is mainly attributed to the decomposition of calcium hydroxide, and this phenomenon usually takes place in the temperature range between 450 to 500 °C [Bentz. 2000; Zhang and Bicanic. 2002].

In this laboratory study, increasing the mechanical properties of GBFS GPC containing NS and POFs 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.

In Iran, many researches have been done regarding road pavement concrete. In this regard, the addition of nano-silica in the composition of concrete has improved the strength [Shirgir et al. 2019], on the other hand, the size of the aggregates has a direct effect on the strength of pavement concrete [Ataei et al. 2016; Choubdar et al. 2021], the addition of steel slag and [Amouzadeh Omrani et al. 2020] Fibers [Pedram et al. 2022; Mansourian et al. 2022] (Pedram 2022, Mansourian 2022) added to pavement concrete have led to the improvement of mechanical properties in this type of concrete.

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 GBFS was used in powder form with the density of 2.79 g/cm^3 according to ASTM C989/C989M standard. The chemical properties of these materials are indicated in Table 1. The NS particles made up of 99.5% SiO_2 with an average diameter in the range of 15 to 25 nm were used. Crimped POFs 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 GPC curing has been performed at 60 °C according to the GPC standards extracted from prestigious articles in this field.

Table1. Chemical Compositions of Materials

Component (%)	GBFS (%)	OPC (%)
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
LOI	0.3	1.84

Tensile Strength (N/mm^2)	>500
Length (mm)	30
Diameter (mm)	0.8
Elasticity Modulus (GPa)	>11
Density (g/cm^3)	0.910

Figure 1. Physical Properties of the POFs

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 GPC with different NS and POFs. The GPC samples are generally categorized into two groups: the first group lacks POFs with the NS amount of 0-8%. The second group contains 8% of NS, where the POFs 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 AAS is used in this case.

The used AAS 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 [Pilehvar et al. 2018]. The samples mixture design is indicated in Table 2. Figure 2 shows the concrete production flowchart based on the concrete mixing design.

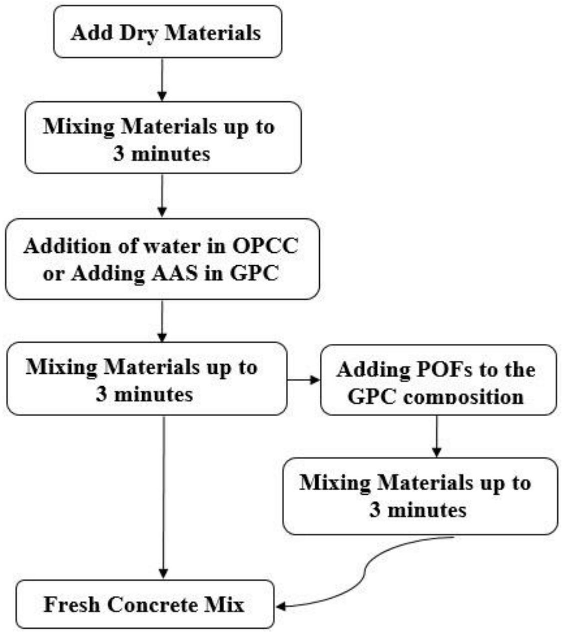

Figure 2. Flowchart of Concrete Production Steps

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 [Kong and Sanjayan. 2010]. In the following, the required experiments were conducted on the concrete samples, according to the related standards.

Table 2. Details of the Mix Designs

Mix ID	Cement	GBFS	Water	AAS	NS	Coarse Aggregates	Fine Aggregates	POFs	Super Plasticizer
	(Kg/m^3)								
OPCC	450	0	202.5	0	0	1000	761	0	6.75
GPCNS0PO0	0	450	0	202.5	0	1000	816	0	6.75
GPCNS4PO0	0	432	0	202.5	18	1000	767	0	7.8
GPCNS8PO0	0	414	0	202.5	36	1000	718	0	8.3
GPCNS8PO1	0	432	0	202.5	36	1000	672	24	8.6
GPCNS8PO2	0	432	0	202.5	36	1000	646	48	9

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. Modulus of elasticity test according to ASTM C469 standard was performed on cylindrical specimens (15 cm in diameter and 30 cm in length). The UPV tests were conducted according to ASTM C597 using a non-destructive ultrasonic electronic apparatus, PUNDIT MODEL PC1012, with an accuracy of ±0.1 μs for a transformator with a vibrational frequency of 55 kHz and a movement time accuracy of ±2% for the distance.

3. Results and Discussion

3.1. Results of the Tensile Strength Test

The results of the tensile strength test of concrete samples at 20 ℃ and 500 ℃ temperature are shown in Figure 3. Figure 4 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 GPC after heating at 500 °C belong to the OPCCNS0PO0 and GPCNS8PO2 designs of 2.47 and 4.73 MPa, respectively. The strength increase is approximately 91% for the GPCNS8PO2 design compared to the OPCCNS0PO0 design. The sample was exposed to heat after the samples were exposed to heat. The maximum increase in strength belongs to the GPCNS8PO2 design by 36% compared to the GPCNS0PO0 design of GPC.

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 OPC design and GPCNS8PO1 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 OPCC and GPCNS8PO1 designs by 51 and 12%, respectively.

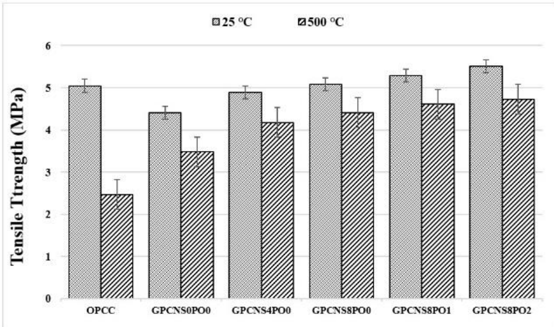

Figure 3. The Tensile Strength of the Specimens

Figure 4. Concrete Specimen after Tensile Strength Test

3.2. Results of the Modulus of Elasticity Test

The results of the modulus of elasticity test of concrete samples at 20 ℃ and 500 ℃ temperature are shown in Figure 5. Figure 6 shows the concrete sample after the modulus of elasticity test.

The minimum and maximum modulus of elasticity obtained from the samples of control concrete and GPC at a temperature of 500 °C belong to OPCC and GPCN8PO2 at 13.3 and 28.01 GPa, respectively, this increase in strength by approximately 1.1 times for the design. GPCNS8PO1 contains GPC compared to conventional concrete design.

Increasing the fibers in GPCNS8PO1 and GPCNS8PO2 mixing designs, compared to GPCNS8PO0 GPC design, has increased the modulus of elasticity as expected. The maximum increase in modulus of elasticity belongs to the GPCNS8PO2 design, which is 38% more than the 2-GPC design. The maximum and minimum modulus of elasticity of the obtained 90-day concrete sample after heating compared to 90-day concrete samples at room temperature belong to OPCC design and GPCNS8PO1 design by 59% and 32%, respectively.

It is generally reported that GPCs that are cured at high temperatures have a lower modulus of elasticity than normal concrete. For each GPC design, we see an increase in the modulus of elasticity in concrete with increasing consumption of NS and fibers. The highest and lowest percentages of reduction in modulus of elasticity of heat-treated concrete belong to OPCC and GPCNS8PO1 at 59 and 32%, respectively.

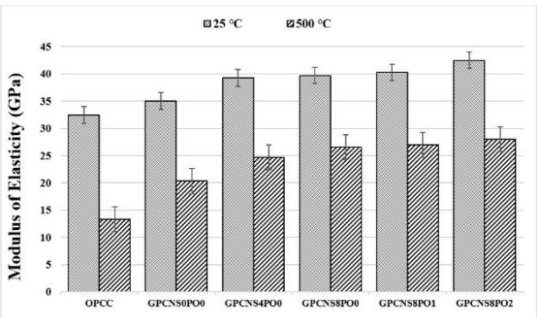

Figure 5. The Modulus of Elasticity of the Specimens

Figure 6. Concrete Specimen Undergoing Modulus of Elasticity test

3.3. Results of the Ultrasonic Pulse Velocity (UPV) Test

The results of the UPV test of concrete samples at 20 ℃ and 500 ℃ temperature are shown in Figure 7. Ultrasonic wave velocities are higher in control concrete samples than in GPC samples. This is due to the formation of microcracks in the heat treatment process (60 ℃) in GPC, which has caused a drop in UPV in these samples.

Nevertheless, these cracks had very fine dimensions and could only influence the UPV having no remarkable effect on the compressive strength of the specimens [Ren et al. 2016]. The application of heat to the concrete specimens caused a drop in UPV. In this regard, the lowest (37.26%) and highest (45.93%) rate of deceleration belonged to OPCC and GPCNS0PO0, respectively.

Addition of NS improved UPV results. In research Improved UPV have been reported with the use of NS in GPC [Ekinci et al. 2019]. The addition of fibers has reduced the UPV results, however the small effect of fibers on the pulse velocity was also reported by Sahmaran et al. They attributed the negligible changes in the pulse velocity to the uniformity of the concrete matrix in all mixtures [Sahmaran et al. 2005]. Based on concrete quality classification in UPV test [Aïtcin. 1998].

The results of UPV in OPCC and the temperature of 20 ℃ are in the excellent range.

Based on this classification as long as the UPV values are classified as "excellent", the concrete has no large cracks or pores that can affect the integrity of the specimen structure [Kwan et al. 2012].

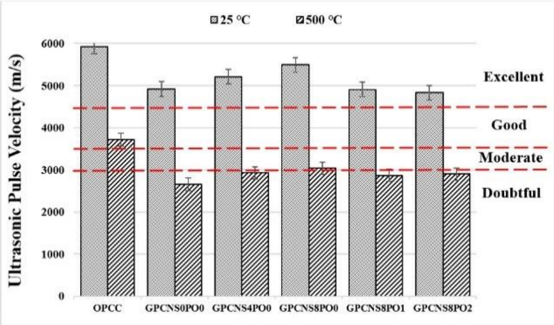

Figure 7. The UPV of the Specimens

3.4. Results of the SEM Analysis

In this study, scanning electron microscopy images at a scale of 50 µm at a 90-day curing age are shown on concrete samples under room temperature in Figure 8 and under high temperature in Figure 9.

According to these images, the concrete microstructure in all mixing designs can be divided into three separate and different basic phases. In this regard, the first phase includes hydration and geopolymization products containing hydrated gels due to the reactivity process. The second phase consists of unreacted crystals that are the result of impurities in the raw materials or unreacted particles in the reactivity process, and are mostly white in the images. The third phase consists of how the cement paste is bonded to the aggregate in the interfacial transition zone. In the samples at room temperature, based on SEM images, it is observed that the largest volume of cavities, pores and inhomogeneous structure belongs to the concrete of plan 1, including control concrete (containing Portland cement), as well as tree structure and small unhydrated crystals (most areas in white) is more visible in this design than other designs, which indicates the low participation of cement particles in the process of chemical composition. In GPC, with increasing consumption of NS in designs, we see more density and coherence in the composition of geopolymer mortar and a decrease in the amount of pores and pores, this is due to the development of geopolymerization process and the formation of more hydrated gels (including dark areas) such as Hydrated calcium aluminosilicate, hydrated sodium aluminosilicate and hydrated calcium silicate in the composition of geopolymer mortar, which has caused homogeneity, bonding of fracture surfaces and strengthening of interfacial and interlayer transition areas in the geopolymer cement matrix.

In Portland cement, C-S-H gel consists of silicone and geopolymer groups of materials with high polymerization and Aluminosilicate structure [Supit et al. 2015]. In the sample containing NS, very few fine cracks are observed, in which NS acts as a filler to fill the spaces inside the hardened microstructure skeleton of the geopolymer paste and increase its compaction [Deb et al. 2015; Shih et al. 2006]. 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 [Assaedi et al. 2019]. In fact, the pozzolanic reaction condenses and homogenizes the microstructures by converting C-H to C-S-H [Du et al. 2015], thus creating more geopolymer gel and a denser matrix [Phoo-ngernkham et al. 2019] However, further increase in NS content causes insufficient dispersion and accumulation of NS particles, which slightly reduces matrix density [Supit et al. 2015].

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. In SEM images, the weakness of the microstructure of concrete exposed to high temperatures is evident due to the decrease in the levels of hydrated gels (dark surfaces) and the increase of cavities and unreacted particle masses (white masses). Pores and cavities in concrete play an important role in reducing they play the mechanical properties 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 [Ryu et al. 2013; Mehdipour et al. 2020]. GPCs resistance in encountering a significant level of heating treatment depends on its constituent chemical compounds and also the temperature and the way of curing [Türkmen et al. 2013]. The OH hydroxyl groups are evaporated at 500 °C. The dihydroxylation changes the Aluminosilicate structure, reducing the resistance level [Kong and Sanjayan. 2010].

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 [Whitehurst. 1951].

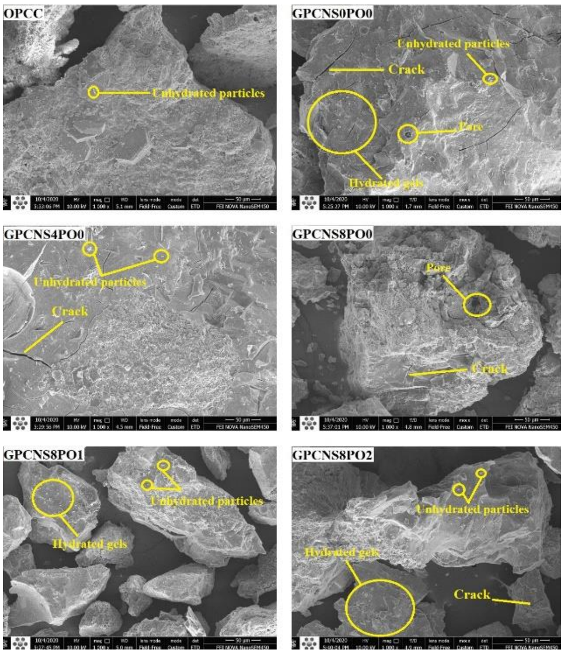

Figure 8. SEM Images under Room Temperature

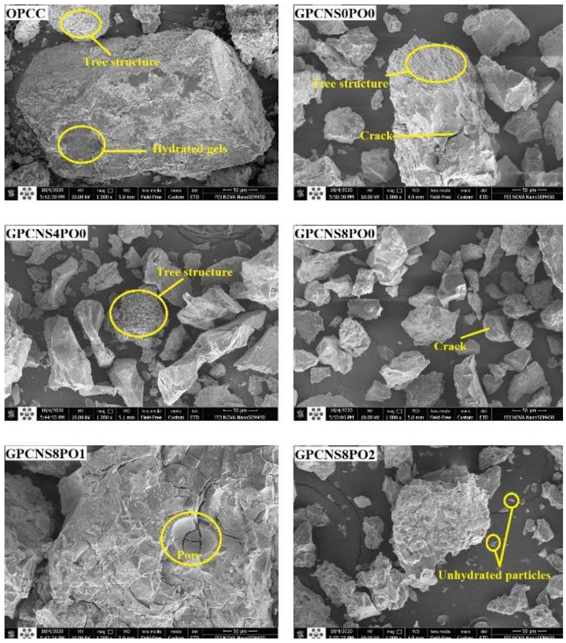

Figure 9. SEM Images under High Temperature

4. Conclusions

In this experimental study, tensile strength, modulus of elasticity and UPV in OPCC and GPC at 90 days of curing at 20% and 500% were investigated. The results of this research are as follows.

1. At a temperature of 20 ℃, the lowest (32.44 GPa) and highest (42.51 GPa) modulus of elasticity belong to design concrete 1 (including OPCC) and design 6 (including GPC containing 8% NS and 2% POFs). The lowest (4.41 MPa) and the highest (5.51 MPa) tensile strength belong to Scheme 2 (including NS-free GPC) and Scheme 6 (including GPC containing 2% POFs). The lowest (4830 m/s) and maximum (5930 m/s) UPV levels belong to plan 6 and plan 1.

2. At a temperature of 500 ℃, the lowest (13.3 GPa) and maximum (28.01 GPa) modulus of elasticity belong to design concrete 1 (including ordinary concrete) and design 6 (including GPC containing 8% NS and 2% POFs). The lowest (2.47 MPa) and the highest (4.73 MPa) tensile strength belong to design 1 and design 6 (including GPC containing 2% POFs). The lowest (2660 m/s) and highest (3720 m/s) UPV levels belong to plan 2 and plan 1.

3. Applying high heat to GPC samples reduced the modulus of elasticity by 42%, tensile strength by 21% and UPV by 46%. The effect of heat on the drop in results in control concrete is more than GPC.
4. The results of all tests at 20 ℃ and 500 ℃ showed the superiority of mechanical properties in GPC compared to OPCC.
5. SEM images, due to the microstructural superiority of GPC over control concrete, covered the results of other tests in this study.

5. Abbreviations

OPC: Ordinary Portland Cement
OPCC: Ordinary Portland Cement Concrete
GPC: Geopolymer Concrete
GBFS: Granulated Blast Furnace Slag
POFs: Polyolefin Fibers
NS: Nano Silica
UPV: Ultrasonic Pulse Velocity
SEM: Scanning Electron Microscope
AAS: Active Alkali Solution

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