Challenge Journal of Structural Mechanics

Research Article

Potential improvement of clinker sand in the mechanical high temperature and transport properties with GGBS-based prepacked geopolymer composite

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ABSTRACT

In this study, a new generation prepacked geopolymer composite (PGC) material that can meet different needs was obtained by combining geopolymer concrete (GPC) and prepacked aggregate concrete (PAC) technology. In the production of PGC, 5-8 mm quartz aggregates were placed in molds and, geopolymer mortar was injected between these aggregates. Aluminosilicate based blast furnace slag (GBFS) was used as binding in geopolymer mortars; sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) was used as alkali activator. In addition, clinker aggregate in different proportions was used as fine aggregate (0–4 mm) in the production of mortar. Within the scope of the study, the physical, mechanical, permeability and high temperature resistance properties of PGC were investigated. The produced samples were cured at 30 and 60 °C for 6 and 8 hours. Hardened unit weights of PGC vary between 2342 and 2539 kg/m^3, and sorptivity values vary between 0 and 0.04 kg/m^2.min$^{0.5}$. While the increase in curing temperature and curing time increases the hardened unit weight values, it decreased permeability values. While the increase of clinker aggregate in the mortar phase does not change the hardened unit weight, it significantly reduced permeability. When the PGC samples are cured at 30 °C, the compressive strengths are 20.38–39.03 MPa; when curing at 60 °C, the compressive strengths are 35.21–57.04 MPa. Flexural strengths, 2.35–6.96 MPa with 30 °C cure, achieved 4.27–9.93 MPa results with 60 °C curing. Increasing the curing time and curing temperature significantly increased the compressive and flexural strengths. The increase in the amount of clinker aggregate added to the mortar phase decreased the strength values. While the compressive strength values of PGC mixtures do not fall below 15 MPa after being exposed to 300 °C high temperature; after the application of 600 °C high temperature, it lost up to 70% of its strength. Increasing the curing time and curing temperature, increased the high temperature resistance. The increase in the amount of clinker aggregate in the mixtures, decreased the strength loss rate.

ARTICLE INFO

Article history:
Received 21 April 2023
Revised 19 June 2023
Accepted 10 July 2023

Keywords:
Clinker aggregate
Composite material
Geopolymer concrete
High temperature
Mechanical properties
Prepacked aggregate concrete

1. Introduction

Ordinary Portland cement has a plastic consistency at first as a result of mixing cement, aggregate and water and, it gains strength and hardens over time (Aïtcin 2000). Concrete is one of the most preferred materials in construction systems, due to the reasons such as being able to give the desired shape in the fresh state, ease of transportation of its components and being economical (Khayat 1999; Meyer 2009). In addition to these advantages, it has been determined by previous studies that cement, which provides binding and strength to

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ISSN: 2149-8024 / DOI: https://doi.org/10.20528/cjsmec.2023.03.002

concrete, releases a high rate of CO_2 gas during the production process (Worrell et al. 2001; Barcelo et al. 2014). It is known that CO_2 emission is one of the main causes of global warming. It has been revealed that in the production of one ton of Portland cement (PC), almost 1 ton of CO_2 is released and, considering the "Mineral Raw Material Products Report" prepared by the US Geological Survey Department in 2023, around 4,1 billion tons of cement was produced in 2022 (Benhelal et al. 2013; Golewski 2021). The importance of the amount of CO_2 released to the atmosphere is clear. It has been revealed by scientists that, PC is responsible for about 10% of global CO_2 emissions (Suhendro 2014; Winnefeld et al. 2022). In order to eliminate the mentioned disadvantage, "geopolymer concrete" which is a more environmentally friendly and sustainable type of concrete, has been the focus of attention of researchers in recent years (Amran et al. 2021; Wasim et al. 2021). In the production of geopolymer concrete (GPC), inorganic materials such as blast furnace slag (GBFS) and fly ash (FA) are generally used as binders instead of cement used as binder in ordinary Portland cement (OPC). In addition, in recent years, different alumina silicate-based inorganic materials such as silica fume, rice husk ash, metakaolin and volcanic glasses have been used in the production of geopolymers (Ahmed et al. 2022; Jindal et al. 2022). The majority of these binders are obtained through the recycling of industrial wastes and approximately 80% less CO_2 is released into the atmosphere compared to Portland cement (PC) (van Deventer et al. 2010; Zhang et al. 2020). By activating the inorganic materials used in the production of GPC with alkalis such as sodium hydroxide (NaOH), sodium silicate ($nSiO_2Na_2O$), it gains binding property as a result of geopolymerization reactions. As a result of these reactions, N-A-S-H in amorphous structure and zeolite in $(NaAlO_2)_7(SiO_2)_9$ structure are formed (Khalid et al. 2019; Krishna et al. 2021). Geopolymer has advantages such as fast hardening, high compressive strength, high acid and fire resistance, low thermal conductivity, low shrinkage, depending on curing conditions and the raw material selection; as well as causing less environmental pollution and producing less energy. The mentioned properties of GPC depend on many factors such as type and content of inorganic material used, type of activator, amount and type of aggregate, curing temperature and curing time (Mohammed et al. 2021; Raza et al. 2022).

Prepacked aggregate concrete (PAC) is a particular type of concrete produced by injecting mortar or cement paste on it after the aggregates are placed in the mold with maximum compactness (Wakeley and Roy 1983). PAC can be preferred in cases where it is difficult to reach, difficult to make molds, and difficult to pour and compact the concrete. In addition, In addition, PAC is preferred in underwater concrete and repair works due to its low shrinkage and high impermeability (Cheng et al. 2019). The coarse aggregate volume in the PAC is around 65-70% and the remaining voids are filled with flowing mortar (de Castro and de Brito 2013). In this type of concrete, the aggregate mix has a discrete granulometry. Thus, it is ensured that coarse aggregated particles come into contact with one another and that there is enough space between the particles to be filled with dough or mortar. PAC contains more coarse aggregate than normal concrete. Therefore, especially the modulus of elasticity is higher than that of normal concrete, and the drying shrinkage is lower (Das et al. 2021). In PAC, the aggregates are in direct contact. That is, they are in grain-grain contact that can cause stress distribution throughout the aggregates (Domingo-Cabo et al. 2009). Since both the coarse aggregates are in contact and the injection paste or mortar completely fills the spaces between the aggregates, the permeability of the prepackaged concrete with a very low void ratio is also very low, and therefore, its resistance to freeze-thaw and chemical attacks is high. Another advantage is that when applied on old concrete in repair works, its adherence is quite good. This is because the fluid paste or mortar used effectively penetrates the voids of the previously roughened concrete surface (Lv et al. 2020). Due to the very low shrinkage of the Prepacked aggregate concrete, the stresses that will occur at the interface are minimized and an effective adhesion, is provided between the two concretes. In addition, in concretes that will act as a shield against nuclear radiation, PAC application in which heavy coarse aggregate and fine aggregate are placed separately, can be advantageous in order to prevent segregation (Yoon et al. 2020).

A variety of studies have been undertaken to examine the effects of concrete under high temperature. According to these studies, when the concrete reaches a temperature of 200 °C, the water in the cavities is removed from the cracks by evaporation. Thus, the water pressure in the concrete decreases, and as the expansion decreases and, the distance between the atoms becomes shorter. As a result, the compressive strength of the concrete increases somewhat as the water escapes (Noumowe 2005; Behnood and Ghandehari 2009). The temperature is above 400 degrees Celsius, as the $Ca(OH)_2$ structure begins to decompose, the cracks in the concrete increase and its strength decreases (Huo et al. 2009). As the temperature of the concrete exceeds 600 °C, the aggregates in it begin to expand. As a result of this expansion, cracks occur as parasitic stresses occur in the concrete. As the temperature and degree of exposure of the concrete increase, the compressive strength of the concrete decreases with the increase in the number and width of these cracks (Schneider 1988; Sukontasukkul et al. 2010). When the temperature reaches 1000 - 1200 °C, the dehydrated phases in the CSH structure which is the basic skeleton of concrete strength, deteriorate. After this temperature, the concrete loses its strength and loses its carrier property (Chan et al. 1999; Arioz 2009). Although studies have been conducted recently to examine the mechanical and durability properties of geopolymer concretes, research on high temperature resistance has been more limited. It has been found that GPC has a greater ability to resist microstructural damage exposure to elevated temperatures than conventional mortars and concrete. The pores of the GPC in the gel and matrix limit the transport of water vapor when exposed to high temperatures, so the high temperature resistance of geopolymer concrete is more stable than OPC (Aredes et al. 2015; Samal 2019). The size and connection form

of the pores in the internal structure of GPC are similar to those that determine its mechanical and durability properties (Gültekin et al. 2022).

Concrete is basically a composite construction material composed of aggregates and paste phase. When concrete is examined in the microstructure, it is known that apart from these two phases, it is an interfacial transition zone (ITZ) (Aydin et al. 2007). The pores, cracks and voids in the concrete are concentrated in the ITZ onto the aggregate surface. The formation of cracks due to stresses in the concrete under load spreads starting from here. The strength and durability properties of concrete are closely related to the interface region. Since the mechanical strength of ITZ is lower than that of aggregate and paste, researchers have extensively studied the behavior of this region. As a result of the researches, properties such as the diameter, roughness, mineral structure of the aggregate, both the water/cement ratio and the type of cement, affect the microstructure of ITZ (Prokopski and Halbiniak 2000; Aldanmaz 2020). The addition of inorganic pozzolans such as fly ash, silica fume and blast furnace slag to the concrete mix, not only contributes to the hydration reaction, but also enhances mechanical and durability properties of concrete decreasing the porosity of ITZ (Topçu and Canbaz 2008). Apart from this method mentioned, using active aggregate also provides positive contributions to the concrete (Beshr et al. 2003; Titi and Tabatabai 2018). Portland cement clinker has also been observed to be used as an active aggregate because of its hydrated formation properties in the presence of water. There are studies showing that when clinker is used as an alternative to natural aggregate, the compressive strength increases, chlorine permeability and diffusion coefficient decrease with the increase in the interfacial phase (ITZ) compaction (Berger 1974; Shafaghat and Allahverdi 2019).

In this study, prepacked geopolymer composite (PGC) was produced by using PC clinker instead of fine aggregate. By applying two different curing temperatures (30–60 °C) to PGC samples instead of the long curing time applied in the literature, a short curing time (6–8 hours), the effects of these parameters on physical, mechanical and permeability values were investigated. Another unique value of the study is the observation of the effect of different high temperature values (300 and 600 °C) on the mechanical strength of PGC.

2. Experimental Work

2.1. Materials

In this study, aluminosilicate-based granulated blast furnace slag (GBFS) used as inorganic binder, was obtained from a local company and it was chosen according to ASTM C989 (2006) standard. The average particle size (d_{50}) of GBFS used in the experiments is 30 μm, its specific weight is 2.78 gr/cm^3, and its specific surface area is 5090 cm^2/g. Sodium silicate (Na_2SiO_3) as well as sodium hydroxide (NaOH) solutions were used for blast furnace slag activation throughout the experiments. Both solutions are in liquid form and, while the specific gravity of Na_2SiO_3 is 1.66 gr/cm^3, it consists of approximately 64% water. NaOH is 99% pure with a solution molarity of 12M. While the specific gravity of NaOH is 1.61 gr/cm^3, 63.9% of the solution consists of water. The ratio between of sodium silicate and sodium hydroxide used in the study is 2.5. The solutions used, were prepared 24 hours before starting the experiments.

In producing PAG, clinker was used instead of fine aggregate with 0–4 mm sieve opening. Clinker was obtained from an OPC manufacturing plant and its specific gravity was 2.96 g/cm^3 and the water absorption rate was 0.5%. In addition, quartz (QA) in sizes (5–8 mm) described as coarse aggregate was used in the study. The specific gravity and water absorption of the quartz aggregate are 2.71 gr/cm^3 and 0.9%, respectively. The chemical and physical properties of GBFS and QA used throughout this study are presented in Table 1, and the XRD pattern of GBFS is presented in Fig. 1. In addition, the materials used during the experiments are shown in Fig. 2.

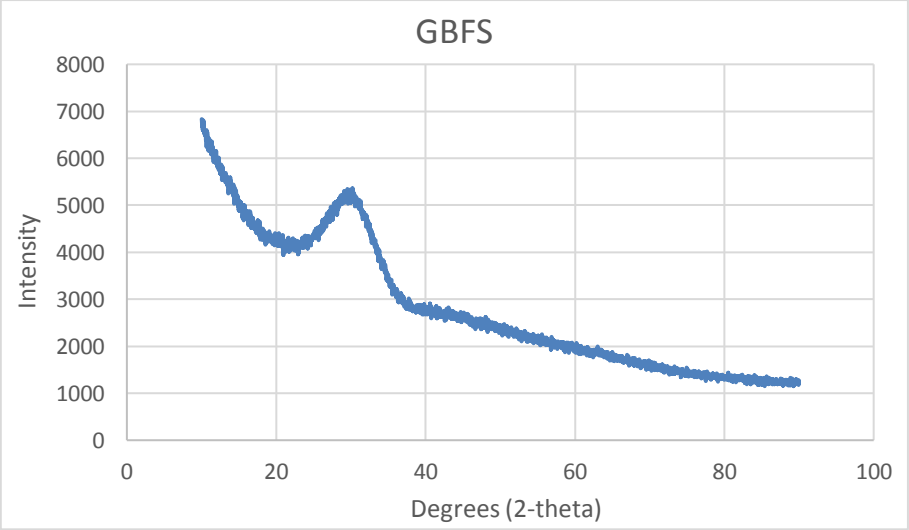

Fig. 1. XRD pattern of GBFS.

Table 1. Chemical, Physical properties of GBFS and QA.

	Oxide	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	LOI*	Specific gravity	Specific surface area
GBFS	%	34.4	37.7	11.4	5.3	6.88	0.8	0	2.96	5090**
QA	%	0.5	98.2	0.08	0.26	0.02	<0.01	0.67	2.71	-

*Loss on ignition; **Blaine method (cm^2/g).

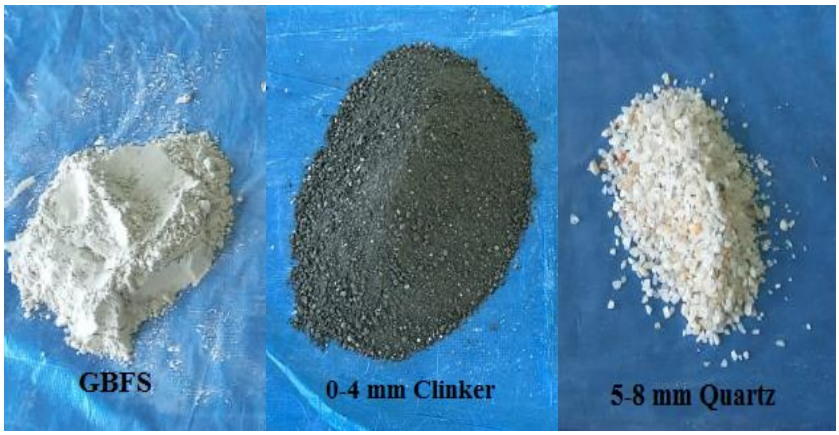

Fig. 2. Used materials in experiments.

2.2. Mixing, casting and curing

Production of PGC samples was done in a stepwise fashion. First, coarse aggregates (QA) were placed in the molds. The amount of QA in all mixtures is constant (800±5 kg/m^3) and, this ratio constitutes approximately 45% of the volume of the mold. On the other hand, a 5 liter Hobart mixer was used to prepare geopolymer mortar. During mortar production, while the amount of GBFS and clinker aggregate varies according to the groups, the amount of NaOH and Na_2SiO_3 was kept constant in all groups. GBFS and 0–4 mm clinkers were first added to the mixer and mixed at low speed for 2 minutes. Then, liquid NaOH was added to the dry ingredients and mixed at low speed for another 2 minutes. Finally, liquid Na_2SiO_3 was added to the mixture and the mortar phase was obtained by mixing at high speed for another 5 minutes. In the production of the mixtures, no superplasticizer and water were added at any stage. While the mortar in the mixer was placed in molds filled with QA, vibration was applied to obtain a homogeneous mixture and to wrap the coarse aggregates in the mortar. The molds of the samples whose production has been completed are wrapped with plastic stretch. In this way, the evaporation of alkalis is prevented during thermal curing. The production process of PGC samples is presented in Fig. 3. Within the scope of this study, 8 different groups were produced and the mixing ratios are given in Table 2. Within the scope of this study, approximately 300 samples were produced depending on the variable experimental parameters.

After the PGC casting was completed, it was placed in the furnace for heat curing with a heating at 5 °C/min and presented in Fig. 4. The samples were subjected to a 6 or 8 hour heat cure at 30 and 60 °C. The samples which completed the curing period, were taken out of the furnace and cooled slowly at room temperature. After the cooled PGC mixtures were removed from their molds, physical and mechanical experiments were carried out.

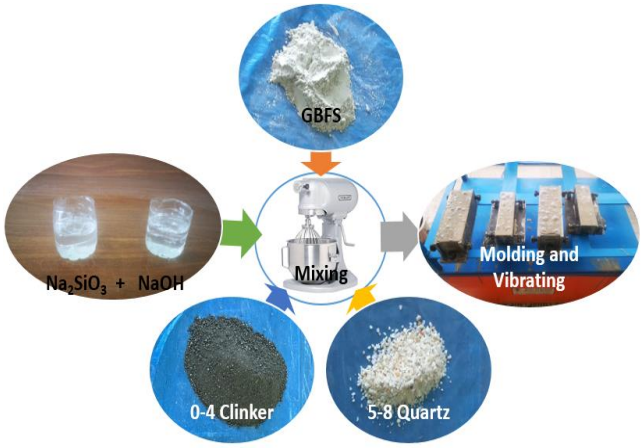

Fig. 3. PGC production process.

2.3. Tests

The hardened unit weights of the PGC samples were measured after heat curing. These were determined in 50×50×50 mm cube samples in accordance with the ASTM C642 (2006) standard based on the Archimedes principle. Capillary absorption of water calculation of PGC mixtures was made according to EN 1015-18 (2002). For these experiments, 50×50×50 mm cubes were produced and the sides of the specimens were covered with silicone. At the end of 24 hours, the amount of water absorbed through capillarity of samples was noted and necessary calculations were made. To determine the strength properties of PGC samples; after heat cure, the samples were three-point flexural test according to

ASTM C348 (2008) and compressive test according to ASTM C349 (2008). The dimensions of the samples produced for flexural strength are 40×40×160 mm, and the dimensions of those produced for compressive strength are 50×50×50 mm. In addition to the physical and mechanical tests applied in this study, the high-temperature resistance of PGC was also measured. The changes in the mechanical properties of the samples were determined after being exposed to high temperatures such as 300 and 600 °C. In the high temperature experiments, 50×50×50 mm cube samples were placed in a laboratory high temperature furnace (Fig. 5) with a heating rate of 10 °C/min. After keeping the PGC samples at the determined high temperature (300 and 600 °C) for 2 hours, they were left to cool at room conditions for 24 hours. As mentioned above, the cooling samples were subjected to compressive tests and their strength changes were measured. In all the experiments mentioned, three samples were tested and, their average values are presented for the accuracy of the results.

Table 2. PGC mixtures.

Mix (kg/m^3)	M1	M2	M3	M4	M5	M6	M7	M8
GBFS	850	800	750	700	650	600	550	500
Clinker (0–4 mm)	150	200	250	300	350	400	450	500
Quartz Ag. (5–8mm)	800	800	800	800	800	800	800	800
NaOH	160	160	160	160	160	160	160	160
Na_2SiO_3	400	400	400	400	400	400	400	400

Fig. 4. 30 °C and 60 °C heat curing of PGC samples.

Fig. 5. High temperature furnace.

3. Results and Discussion

3.1. Physical properties

In Fig. 6(a-b), the hardened unit weights observed after curing the GPC blends at 30 and 60 °C respectively are given. After the measurements, it was determined that the unit weights of the PGC samples were close ones between approximately 2342 and 2539 kg/m^3. This situation can be accepted as an indication that the aggregates are positioned in the mould and the mortar is poured homogeneously. Increasing the curing time from 6 hours to 8 hours at 30 and 60 °C slightly increased the hardened unit weight values. As GBFS grains become more activated later on, it can be interpreted that the chain-structured reaction products increase. It has also been observed that due to the fact that the curing times are close to each other, the results change less. Increasing the curing temperature from 30 °C to 60 °C, the hardened unit weight values increased significantly. This situation was interpreted as the formation of more gel products as a result of geopolymerization reactions. If the impact of curing temperature and curing time on hardened unit weight is examined, it was observed that the increase in curing temperature affected these values more. For example, while the hardened unit weight of the M1 mixture which was cured for 6 hours at 30 °C was 2352 kg/m^3, this value was measured as 2359.4 kg/m^3 by increasing the curing time to 8 hours at the same temperature. When the same M1 mixture was cured at 60 °C

for 6 hours, its unit weight reached 2443.2 kg/m^3. Since the same weight of clinker aggregate is added instead of GBFS removed from the mixture, the increase in the amount of clinker aggregate did not change the hardened unit weight much. In addition, the fact that the coarse aggregate and activators were constant in all mixtures was thought to be another reason for the formation of this result.

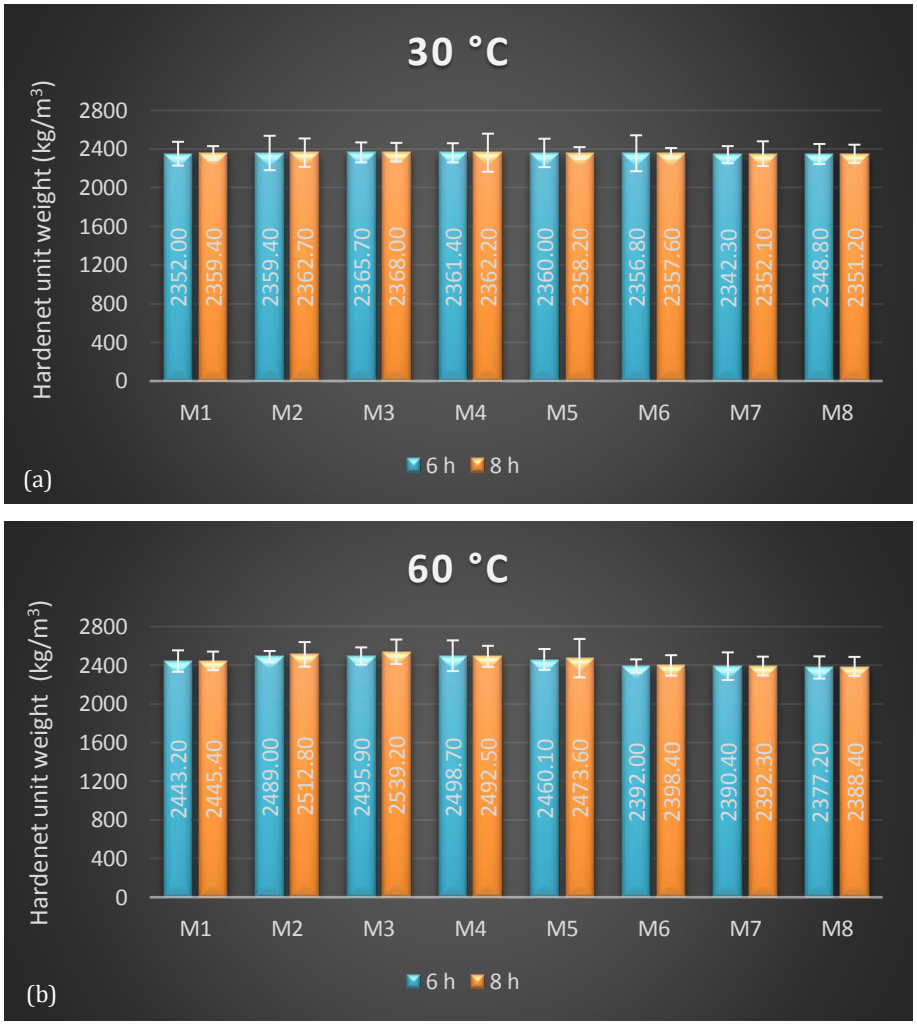

Fig. 6. Hardened unit weights of GPC: (a) 30 °C curing; (b) 60 °C curing.

Öz et al. (2022) added quartz sand in different proportions instead of natural sand to slag and metakaolin based geopolymer concretes. Three different curing times (6, 8 and 10 hours) and three different curing temperatures (40, 60 and 80 °C) were applied to the mixtures they produced. As a result of their measurements, they observed that the hardened unit weights were between 2160 and 2346 kg/m^3. They reported that the cured unit weights decreased with the increase of curing time and curing temperature. They interpreted this result as the evaporation of the activators with the effect of temperature and the lower unit weight of the added quartz aggregate compared to the natural sand. Durak (2022), cured the geopolymer mixture in which fly ash was used as a binder at 100, 200, 300, 400, 500, 600, 700 and 800 °C in 30 and 60 minutes. After a short curing of 30 minutes at 300 °C, satisfactory values like 9.8 MPa flexural and 32,8 MPa compressive strength were observed. In addition, it was emphasized that the cured unit weights of the mixtures decreased with the rise of the curing temperature and time. Albitar et al. (2017) produced geopolymer concrete in which fly ash was used as the precursor, and ordinary Portland cement samples. After exposing the mixtures to acid effect for 9 months, the hardened unit weight changes were examined. As a result of their study, the mass loss of OPC-based concrete was 11% higher than that of geopolymer concrete. They observed from the results that gel products formed as a result of geopolymerization reactions are more resistant to acids than CSH structures in concrete. In their study, Sevinç and Durgun (2020) produced geopolymer concrete by using fly ash, silica fume and glass powder materials in different proportions. They stated that both the fresh and hardened unit weights of the mixtures increased with the increase in the amount of glass powder used and the molarity of the activator. In their experiments, they observed that the hardened unit weight values were between 1920 and 2310 kg/m^3. They stated that the mechanical strength properties of the mixtures with higher hardened unit weights are generally good.

3.2. Mechanical properties

The compressive strength of PGC samples heat treated at 30 °C for 6 and 8 hours is shown in Fig. 7(a). The compressive strength of the samples which were heat cured at 60 °C for 6 and 8 hours, is presented in Fig. 7(b). In the study, the extension of the curing time generally contributed positively to the compressive strength. Extending the curing time indicates that the number of gel products formed in the microstructure increases more. In the groups in which the amount of clinker aggregate increased, the extension of the curing time had less effect on the strength. CSH structures released as a result of the hydration of clinker are formed more slowly than the chain Si-O-Al structures that form the skeleton of the geopolymer. Therefore, increasing the curing time from 6 hours to 8 hours did not affect the strength values much. This result indicates that if geopolymer mixtures are prepared using clinker aggregate, the curing time will be shortened and thus the energy spent for thermal curing will be reduced. In addition, this may be an indication that the clinker aggregate samples will continue to gain strength in advancing ages. Increasing the curing temperature had a positive effect on the strength of the PGC samples. While the compressive strength of the samples cured at 30 °C varies between 20.38 and 39.03 MPa, the compressive strength of the samples cured at 60 °C varies between 35.21 and 57.04 MPa. If the temperature increased from 30 °C to 60 °C, the compressive strength increased between 21% and 47%. This result indicates that the curing temperature of 30 °C is not suitable enough for mixtures. In other words, for the strength of the mortar phase, it can be interpreted that the products of geopolymerization develop better at 60 °C. Another interpretation is that the strength of the matrix surrounding the aggregates is important for the strength of the prepack concrete. In addition, it is seen that the compressive strength values decrease as the amount of clinker aggregate in the PGC mixture increases, that is, from the M1 mixture to M8. It has been explained in the above section that the increase in the amount of clinker aggregates in the mixtures is achieved by decreasing the amount of GFBS. It can be said that the reaction of clinker aggregates with alkali activators is more limited than GFBS which is the reason for the observation of these results. However, considering that this strength loss is at acceptable levels and that clinker aggregates are included in the geopolymerization reactions, it has been determined that this material can be used in the mixture.

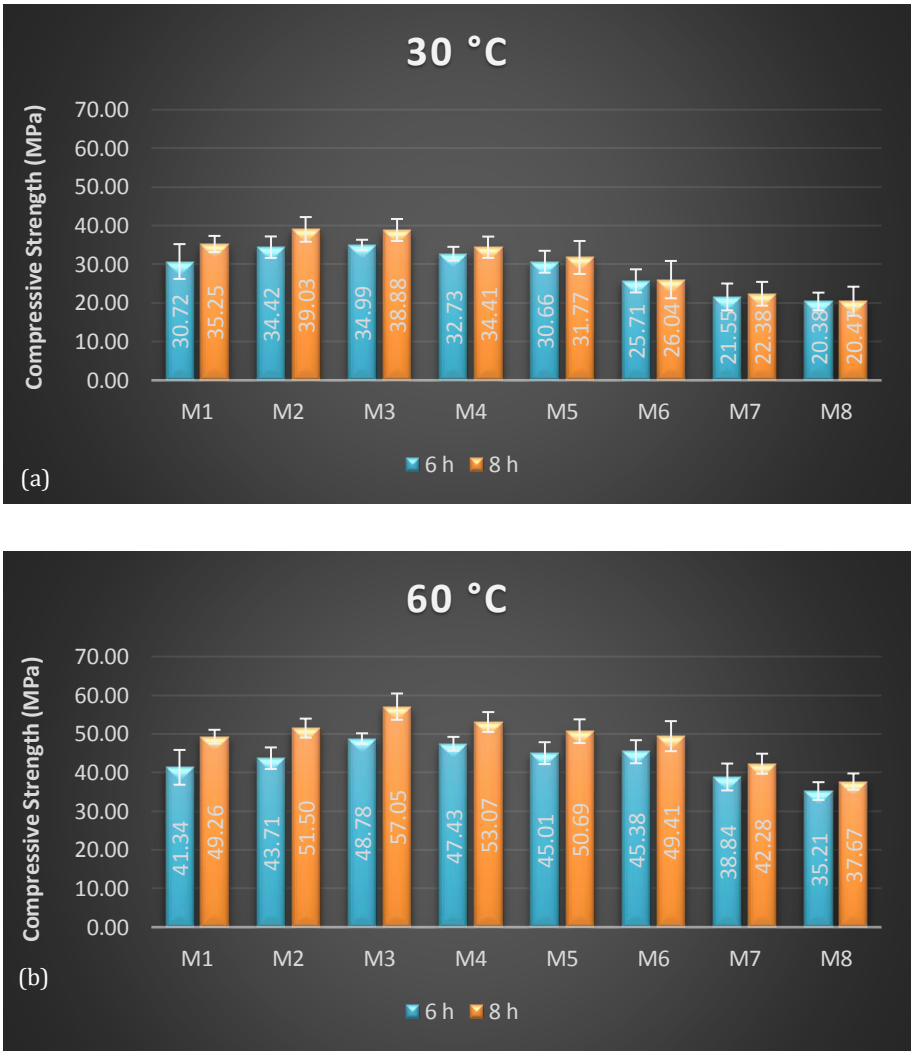

Fig. 7. Compressive strength of GPC: (a) 30 °C curing; (b) 60 °C curing.

Another remarkable result in Fig. 7 is that the compressive strength values increase as one goes from the M1 mixture to the M3 mixture for the whole curing temperature and curing time. When going from M3 to M8, it starts to decrease. The clinker aggregate added to M3 has increased the compaction of the mixture and an ideal aggregate-mortar ratio has been obtained for PGC. When going from M3 to M8 mixture, the strengths decreased by removing the amount of GFBS from the mixture at the rate that the clinker and aggregate increased and this ratio deteriorated. It has been interpreted that the amount of clinker aggregate added to the mixture is effective in the formation of these results.

In Fig. 8(a), the flexural strength results of the PGC samples are presented after curing at 30 °C, and in Fig. 8(b) at 60 °C for 6 and 8 hours. The flexural strength results generally showed parallelism with the compressive strength. As the curing time increases, the flexural strength of the samples increases with a greater rate up to the M4 mixture; after this group, the rate of increase remained at lower levels. The reason for this result is thought to be related to the gel products formed, the density and porous structure of these structures, as explained in the compressive strength. Increasing the curing temperature significantly increased the flexural strengths. While the strength values remained between 2.35–6.96 MPa at 30 °C, the strengths of the samples cured at 60°C reached results such as 4.27–9.93 MPa. Considering that this increase rate is between 20-88%, the role of curing temperature in the flexural strength of PGC samples can be better understood. As the temperature increased from 30 °C to 60 °C, the activity of GBFS grains increased, and it was thought that chain gel products were formed in greater quantity and in a shorter time. Another important finding obtained from the flexural strength result is the comparison of the compressive and flexural strength ratios of the PGC samples with the ratios in ordinary Portland cement. It is known that the ratio of compressive strength to flexural strength in ceramic materials such as concrete generally varies between 1/7 and 1/10. Based on this study and the information in the literature on Prepacked aggregate concrete, it has been observed that this ratio varies between 1/4 and 1/8. In ordinary Portland cement, the aggregates are usually in a discrete form, wrapped in the mortar phase without contacting each other. In addition, the amount of interfacial phase (ITZ) with a porous structure on the aggregate surfaces is high.

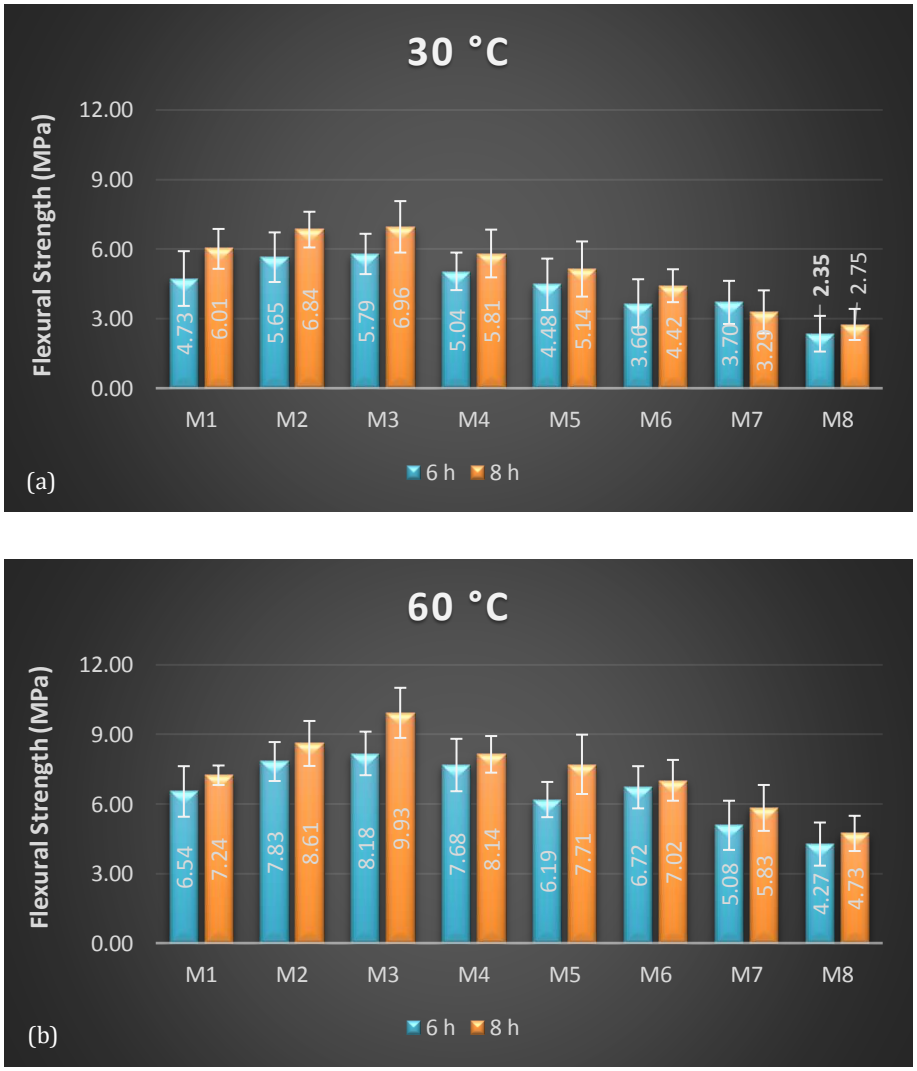

Fig. 8. Flexural strength of GPC: (a) 30 °C curing; (b) 60 °C curing.

In PAC, the amount of ITZ with voids is less than in ordinary Portland cement, because the aggregates with high rigidity come into contact with each other. For this reason, it is known that the flexural strength of prepacked aggregate concrete is relatively higher than that of ordinary Portland cement. The results obtained in this study were similar to this information. Based on this result, in productions where flexural strength is more critical, Prepacked geopolymer composite technology can be a solution. When the test data are examined, another observed result is that the flexural strength decreases somewhat as the amount of clinker aggregate increases. It has been interpreted that the reason for this decrease in flexural strength is similar to the reasons in compressive strength, that is, it is related to the amount of gel product formed in the internal structure. When the results of flexural strengths are examined, it is seen that the strengths increase from M1 to M3 and then begin to decrease under different curing temperatures and curing times. The reason for this situation is due to the aggregate-mortar ratio, as explained in the compressive strength results.

Güzelküçük and Demir (2019) investigated the compressive strength of perlite-based geopolymer concretes depending on the curing time and temperature. According to their results, they emphasized that the highest compressive strength was 46.76 MPa at 110 ºC curing temperature, 24 hours curing time. Hassan et al. (2019) investigated the change of the mechanical properties of geopolymer concretes, in which fly ash was used as binder, depending on the curing temperature. They stated that after applying ambient curing and 70 ºC temperature curing to the mixtures they produced, temperature curing improved the elastic modulus and other mechanical properties of geopolymer concretes. Kaplan et al. (2023) investigated the mechanical properties of Prepacked geopolymer concrete (PAG) mixtures. They reported that, PAG has approximately 70 MPa compressive strength and 5.5 MPa flexural strength values due to its high aggregate content. Verma and Dev (2022), investigated the mechanical strength and microstructure properties of blast furnace slag and fly ash based geopolymer mixtures depending on the curing temperature. According to the data they obtained, with the increase of curing temperature, the mechanical properties of geopolymer concrete such as compression, flexural and splitting tensile increased as well as its internal structure properties. Zhang et al. (2021) searched the mechanical properties of geopolymer concretes, in which they used metakaolin and silane at different dosages, according to different curing times. The geopolymer mixtures they produced were cured at room conditions for 28, 56, 90, 180 and 360 days. As a result of their experiments, the curing of the samples until the 90th day increases the compressive flexural strength; they observed that the strength values did not increase after this period. In their study, they measured the highest compressive strength and flexural strength of 51.4 MPa and 12.93 MPa, respectively, in the mixtures containing 1% by weight silane. Bing-hui et al. (2014) applied different curing temperatures and curing times in order to achieve the highest mechanical strength values of geopolymer concretes, in which metakaolin is used as a binder. They reported that the best compressive strength results were measured in groups cured at 97.95 MPa at 60 °C for 7 days. They stated that increasing the curing temperature and curing time increased the geopolymerization reactions.

3.3. High temperature effect

The measured compressive strengths of PGC samples cured at 30 °C after 300 and 600 °C high temperature application are shown in Fig. 9(a-b); The strength values of the samples cured at 60 °C after the same high temperature effect are shown in Fig. 10(a-b). When Figs. 9 and 10 are examined, the compressive strength of the PGC samples decreased compared to Fig. 7 after both high temperature applications. For example, while the compressive value of the M3 mixture cured for 8 hours at 60 °C which is not exposed to high temperatures, is approximately 57 MPa; after applying a temperature of 300 °C and 600 °C, its strength decreases by 56% and 70%, respectively. The products formed in geopolymer concretes to which GBFS is the binder are NASH and CASH gels. When the temperature is approximately 300 °C, the water in the gel structures starts to evaporate away from the hydroxyl structures. The expansion of the vapors formed and the movement of this steam cause the formation of microcracks in the internal structure. If the duration or degree of temperature is increased, the cracks formed begin to grow. In addition, since the increased temperature values greatly deteriorate the chemical structure of the gel products that make up the skeleton of the mixture, the strength of the specimens decreases. When the results are examined, the compressive strength values of the PGC samples can reach more than 15 MPa after processing at 300 °C; It lost up to 70% strength from the process at 600 °C. These results support the comments made. Another result from this is that the gel structure, which provides resistance at 300 °C, has begun to break down. Dehydration dimensions increased as the temperature reached 600 °C. These decreases in strength values showed changes according to the curing temperature, curing time and the amount of clinker aggregate in the mixtures. When the effect of curing temperature on high temperature resistance is examined, the application of high temperatures (300 and 600 °C) to PGC specimens cured at 30 °C decreased the strength values less than those cured at 60 °C. The lower compressive strength loss of the samples cured at 30 °C was thought to be related to the pozzolanic activity. In these groups, because the pozzolanic activity due to geopolymerization reactions is not completed at low curing temperatures, the gel products continued to form up to a certain temperature value. In PGC mixtures cured at 60 °C, it can be interpreted that almost all of the reaction products are formed. In addition, it was thought that the capillary void content was less in the mixtures cured at 60 °C, and therefore the evaporating water created more vapor pressure and damaged the internal structure. While the compressive strength of PGC mixtures cured at 30 °C varies between 15.21 and 23.35 MPa, the compressive strength of GPC mixtures cured at 60 °C was measured between 17.04 and 25.17 MPa. When the ef-

fect of curing time on high temperature resistance is examined, the strength of the samples with longer curing time after high temperature was higher than the samples with shorter curing time. It was observed that the compressive strength of PGC samples cured for 6 hours changed between 13.02–20.12 MPa after high temperature, and the samples cured for 8 hours changed between 12.53–25.17 MPa. The longer the curing time, the better the high temperature post-temperature resistance of the samples with longer curing time, as more geopolymerization reactions take place and accordingly more gel products are formed. The data obtained as a result of the experiments show parallelism with the comments. If the effect of the amount of clinker aggregate in the mixture on the high temperature resistance is examined, when Figs. 9 and 10 are examined, the strength loss rate of the samples decreased with the increase in the amount of clinker aggregate. For example, M1 mixture containing 150 kg/m^3 of clinker aggregate, cured at 60 °C for 8 hours, is 57% at 300 °C; at 600 °C, it lost 69% of its strength. In the M8 mixture containing the highest amount of clinker aggregate (500 kg/m^3), these rates were around 52% and 62%, respectively. It has been explained in the previous section with the reasons why the increase in the amount of clinker aggregate decreases the compressive strength. However, when the results of compressive strengths after the effect of high temperature are examined, increasing the amount of clinker aggregate decreased the strength loss rate. The structures of clinker aggregates are more porous than GBFS, therefore, mixtures with clinker aggregates have become porous. As the amount of clinker increased, the porosity ratio in the indirectly produced mixtures increased. Having more pores means creating more capillary spaces in the mixture. The water vapor formed in the internal structure of the PGC mixtures due to the effect of high temperature leaves the sample by advancing in the capillary spaces without damaging the matrix. However, it is known that the clinker aggregate has a $CaCO_3$ structure and this structure is dehydrated at high temperatures such as 900 °C. It should not be overlooked that this may be another reason why PGC samples with clinker aggregates experience less strength loss after high temperature.

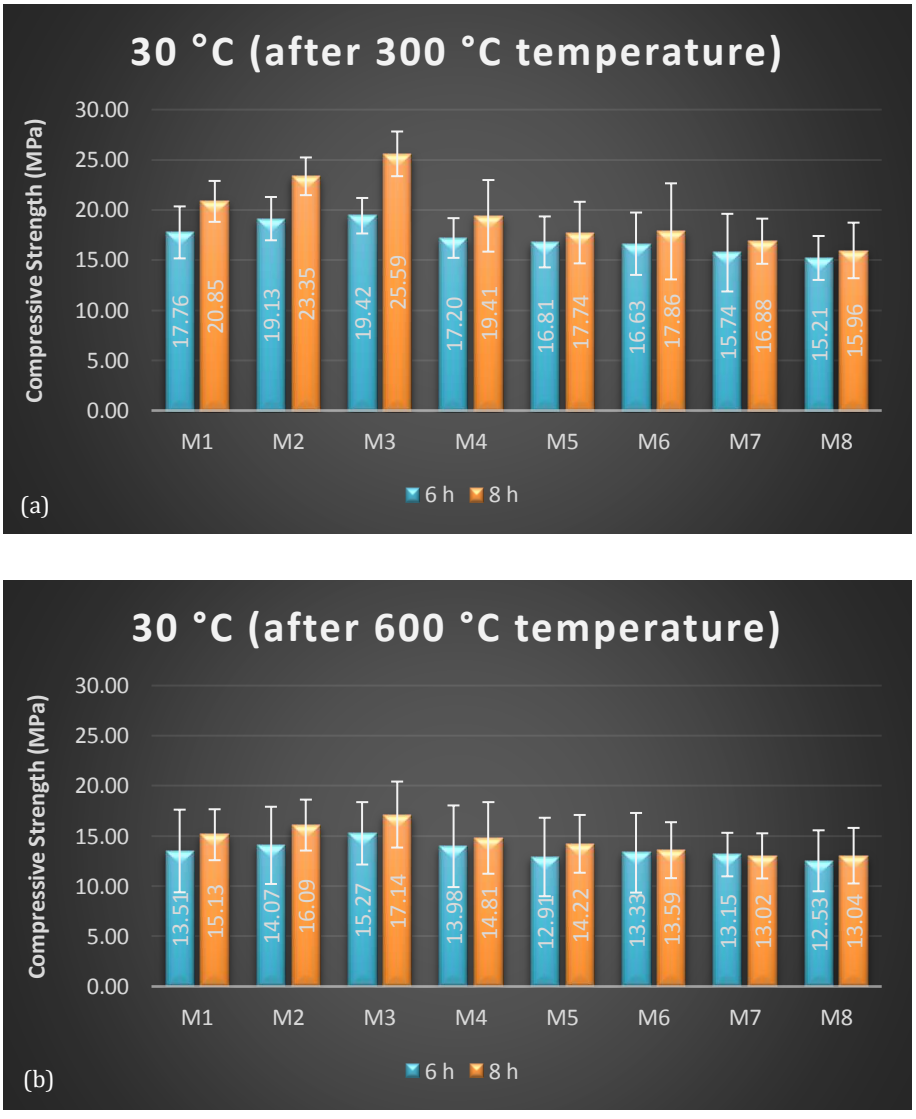

Fig. 9. Compressive strengths of PGC samples cured at 30 °C: (a) after 300 °C; (b) after 600 °C.

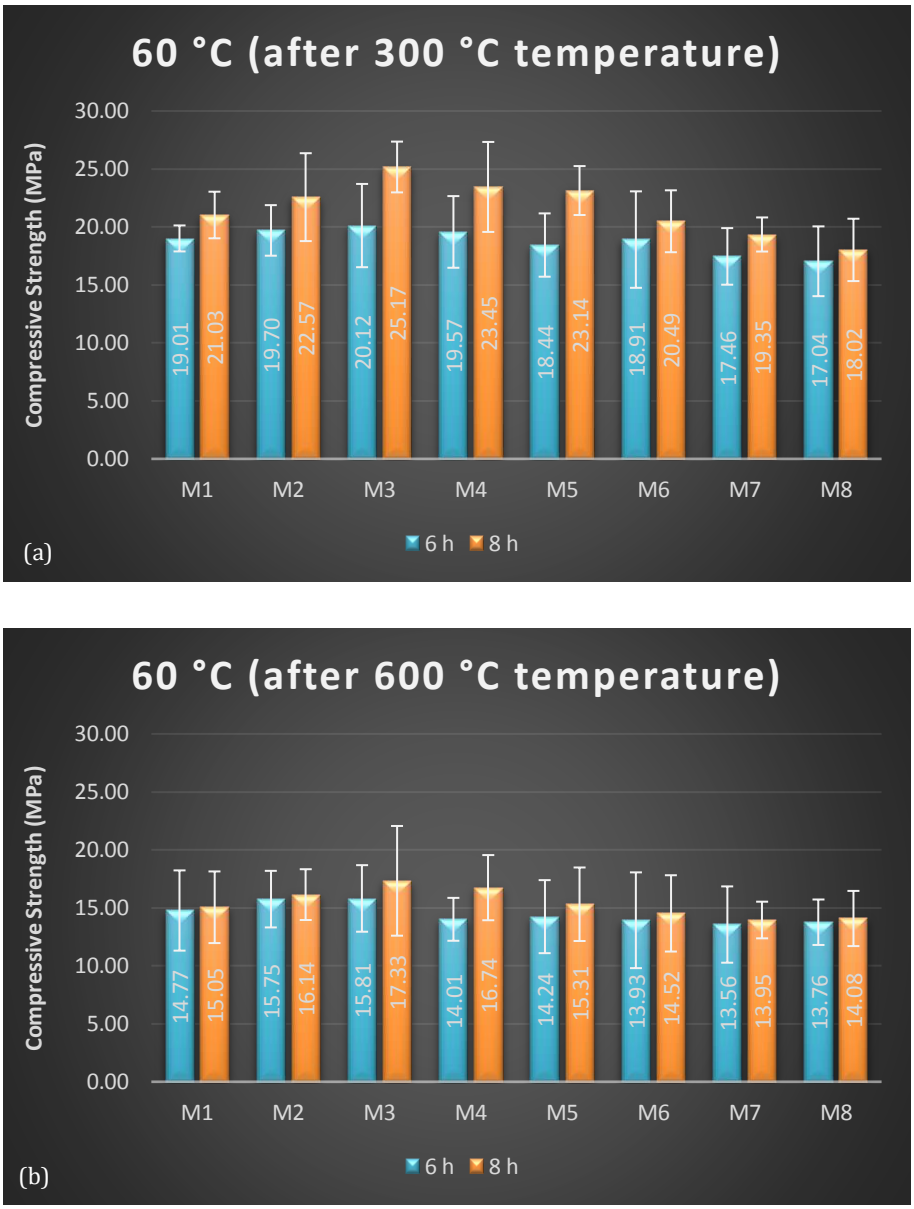

Fig. 10. Compressive strengths of PGC samples cured at 60 °C: (a) after 300 °C; (b) after 600 °C.

Nuaklong et al. (2021) used 25% and 50% by weight waste granite instead of river sand in the geopolymer mixture in their study. High temperature resistance was investigated by including fine aggregates in the mixture as saturated surface dry (SSD), air-dry (AD) and oven-dry (OD). As a result of their experiments, they determined that the waste granite geopolymer concrete showed a spalling behavior similar to that made from completely natural sand. In addition, they stated that due to the formation of capillary voids in the structure of dried aggregates, less strength loss was observed in these mixtures after high temperature. Tayeh et al. (2021) have produced lightweight geopolymer concrete in which fly ash and blast furnace slag are precursors. They investigated the mechanical behavior of these mixtures after high temperature using natural pumice and lightweight expanded clay aggregates in their mixtures. As a result of their experiments, they observed that the aggregates they used exhibited less strength loss than the mixtures using dolomite aggregate. They emphasized that the formation of this result is due to the hollow structures of natural pumice and expanded clay. Hager et al. (2021) applied high temperature up to 1000 °C to the geopolymer mortar samples they produced by adding blast furnace slag in different weight ratios instead of fly ash. They observed that with the temperature reaching 200 °C, the compressive strength increased by 30% and the flexural strength doubled. They determined that the strength values due to the deterioration of the internal structure decreased to 90% when the temperature reached 1000 °C. Kürklü, (2016) investigated the high temperature resistance of geopolymer concretes cured at 60 °C for 5, 24, 48 and 168 hours. After his experiments, he observed the highest flexural strength for 5 hours and the highest compressive strength for the mixtures cured for 48 hours. He also stated that 400 °C and 600 °C are critical temperatures for changes in mechanical and physical properties. He noted that with the final temperature value reaching 1000 °C, the strength values dropped significantly. Jaarsveld et al. (2002) investi-

gated the high temperature resistance of fly ash and metakaolin based geopolymer concretes. As a result of their experiments, they determined that the strength of the mixtures exposed to high temperature is closely related to the expansion temperature of the aggregate used. In addition, they emphasized that curing time and curing temperature are other important parameters for the high temperature resistance of geopolymer concretes.

3.4. Sorptivity

Sorptivity is based on the principle of measuring the water penetrating through the voids and cracks in the hardened concrete at certain time intervals. This value can guide the estimation of properties of concrete such as strength, durability and life of concrete. Sorptivity values are presented in Eq. (1). In this equation: C=Capillary water absorption coefficient (kg/m^2.min$^{0.5}$), M1= specimen mass after the immersion for 10 min (kg), M2=specimen mass after the immersion for 24 hours (kg).

$$C = 0.1 \cdot (M_2\text{-}M_1)\ \text{kg}/(\text{m}^2 \cdot (\text{min})^{0,5}) \quad (1)$$

It is calculated by the capillary water absorption coefficient. In Fig. 11 (a-b), capillary absorption of water values of PGC mixtures are presented. When the graphs are examined, the first striking result is that the capillary absorption decreases significantly with increasing curing temperature. Increasing the curing temperature from 30 °C to 60 °C caused the permeability values of the PGC samples to decrease by up to 50%. Increasing the curing temperature increased the geopolymerization degree of the mixture, resulting in more reaction products. Thus, a denser PGC microstructure was obtained, in other words, the porosity was reduced. As the curing temperature increased, the complexity of the matrix phase increased, which was interpreted as a decrease in capillary water absorption measured in the samples. Another remarkable result in Fig. 11 is that the permeability values decrease significantly with the increase of the curing time. The capillary water absorption results of the samples that were heat cured for 8 hours decreased between 15 and 35% compared to the samples cured for 6 hours. While the permeability values of PGC samples cured for 6 hours reached up to 0.04 kg/m^2.min$^{0.5}$; It was measured as 0.022 kg/m^2.min^{0,5} at most in the samples that were cured for 8 hours.

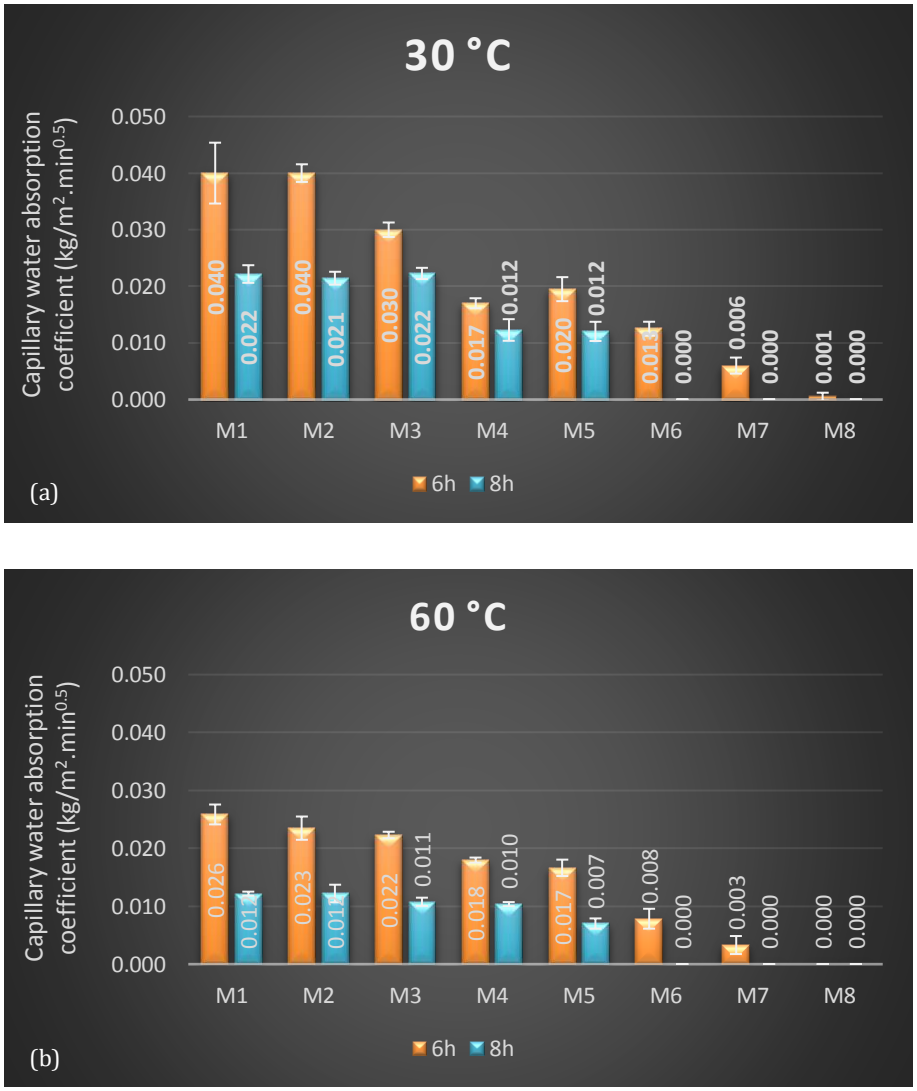

Fig. 11. Capillary water absorption coefficient of GPC: (a) 30 °C curing; (b) 60 °C curing.

It was thought that prolonging the curing time reduced the void ratio in the microstructure of the mixtures, creating more gel products. While examining the compressive and flexural strengths, it was mentioned in the previous section that the extension of the curing time increases the strength values. From this point of view, it is seen that the permeability results are compatible with the mechanical properties. Considering Fig. 11, a final observed result is that the permeability decreases as the amount of clinker aggregate in the mix increases. In fact, increasing the amount of clinker aggregate appears to be the parameter that decreases the capillary water absorption value the most. For example, permeability results in M8 mixture cured at different curing temperatures and times, it is measured as 0 $kg/m^2.min^{0.5}$. Clinker consists of calcium and silicate structures since its aggregates are obtained from OPC. During the permeability test, water molecules diffusing into the PGC samples via capillary are retained by the clinker aggregates. The trapped water molecules begin to hydrate with the clinker aggregates. As a result of these reactions, the porosity decreases as CSH structures are formed and fill the spaces in the internal structure. It was thought that the permeability values of the PGC samples with decreasing porosity decreased with the realization of the mentioned process.

Venkatesan and Pazhani (2016) investigated the strength and durability properties of geopolymer concrete prepared using blast furnace slag (GBFS) and black rice husk ash (BRHA) at different rates. According to the results of their experiments, adding more than 10% BRHA to the mixture reduces the strength values; permeability values decrease. Due to the chemical structure and dimensions of BRHA, filling the voids in the internal structure of the geopolymer concrete caused this situation to occur. Shaikh (2016) investigated the physical, mechanical and durability properties of fly ash based geopolymer concretes by using recycled coarse aggregate (RCA) at different rates. In his study, he observed that the permeability values of the mixtures increased with the increase of recycled coarse aggregate ratio. Due to the operations made during the production process of RCA, cracks occur on its surfaces. For this reason, it was interpreted that the permeability increased in geopolymer mixtures using RCA. Alcan et al. (2023) reported that in the geopolymer concrete they produced using GBFS and metakaolin, the permeability value decreased by 2.45 times as the curing time increased from 4 hours to 8 hours, and the permeability decreased by 81% when the curing temperature increased from 60 °C to 90 °C. Noushini and Castel (2016) investigated the permeability results of fly ash and slag-based geopolymer concretes after three different curing temperatures (60, 75 and 90 °C) and four different curing times (8, 12, 18 and 24 hours). As a result of their experiments, they stated that the mixtures cured at 75 °C for 18-24 hours had the lowest permeability value. They interpreted that lower porosity or less interconnected capillary spaces were formed because more gel products were formed at the mentioned curing temperature and time. Mermerdaş et al. (2017) added three types of aggregates, river sand, crushed limestone, and sand-limestone, to geopolymer concretes in which fly ash was used as binder. In their study, the best flowability was measured in groups with river sand aggregates, the best mechanical strength was measured in groups with limestone aggregates, and the lowest permeability results were measured in groups with sand-limestone aggregates. They observed the permeability value as 0.0222–0.0262 $mm/min^{0.5}$ in the groups where sand-limestone aggregate was used in combination. They interpreted this result as different types of aggregates filled the voids better with particles of various sizes and reduced their pore structures.

4. Conclusions

This study investigated the effects of clinker aggregate Prepacked geopolymer composite (PGC) applied at different curing temperatures and curing times on physical, mechanical and high temperature resistance. Obtained findings are presented below:

- While the curing time increased from 6 hours to 8 hours, the hardened unit weight values increased slightly; increasing the curing temperature from 30 °C to 60 °C increased these values at greater rates. Since clinker aggregate was added to GBFS weight removed from PGC mixture, the effect of clinker aggregate amount on unit weight values is not evident. The M1 mixture cured at 60 °C for 8 hours, with a hardened unit weight value of 2539.2 kg/m^3, the highest value observed.
- The compressive strength of PGC samples increased with increasing curing time and temperature. In particular, increasing the curing temperature from 30 °C to 60 °C made the increases in compressive strength more pronounced. Increasing clinker aggregate ratio, on the other hand, caused a decrease in strength. The highest compressive strength of 57.04 MPa belongs to the M3 mixture, which was cured at 60 °C for 8 hours; the lowest belongs to M8 mixture cured at 20.38 MPa 30 °C for 6 hours.
- The flexural strength results are quite similar to the compressive strength results. As more reaction products were formed with increasing curing temperature and time, the flexural strength increased. The M3 mixture, which is subjected to curing at 60 °C for 8 hours, is the highest value measured with a remarkable value of 9.93 MPa; The M8 mixture, cured at 30 °C for 6 hours with a value of 2.35 MPa, has the lowest flexural strength. The increase in the amount of clinker aggregate caused a decrease in the flexural strength.
- The strength of PGC samples after high temperature is directly proportional to curing temperature and curing time. The increase in clinker aggregates causes the formation of a hollower interior structure. In high temperature application, since the water vapor can move in the capillary spaces, the parasitic stresses are reduced. Thus, the strength loss rate is reduced. After 300 °C and 600 °C high temperature application, the highest strength is 25.17 MPa and 17.33 MPa, respectively, this belongs to the M3 mixture cured at 60 °C for 8 hours. The lowest strength values measured after the same high temperature are 15.21 MPa and

12.53 MPa, and the M8 group cured at 30 °C for 6 hours.

- Permeability values were highly affected by the change of clinker aggregate amount, curing temperature and curing time in the mixture. In case the applied curing temperature increased from 30 °C to 60 °C, the capillary water absorption values decreased significantly. Prolongation of the curing time also caused a similar effect. In PGC samples cured at higher temperature (60 °C) and longer (8 hours), since the porosity in the internal structure decreases; these results have been observed. The increase in the amount of clinker aggregate also decreased the permeability value. Clinker holds the water molecules in the aggregate permeability test and binds them to the calcium and silicate in its structure. As the resulting CSH structure fills the gaps, the internal structure of these groups becomes more compact. The M1 sample, which was cured for 6 hours at 30 °C, has the highest permeability value of 0.04 $kg/m^2.min^{0.5}$. In the M8 mixture cured at 60 °C for 8 hours, this value was measured as 0 $kg/m^2.min^{0.5}$.

This study tried to present a different perspective to the literature by combining Prepacked aggregate and geopolymer concrete technology with the use of clinker aggregate. It has been determined that this innovative type of concrete can be used in works such as underwater concrete casting and repair, and can increase high temperature resistance. The study aims to make the mentioned technology more sustainable by making some suggestions for the authors who will conduct research on this subject in the future.

Acknowledgements

None declared.

Funding

The authors received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

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