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Abstract

2019 fib. International Federation for Structural Concrete The effect of triaxial geogrid reinforcement on the thermal expansion and drying shrinkage of geopolymer concrete (GPC) was experimentally investigated. Three groups of GPC prism specimens with a length of 280 mm and a cross-section of 75 mm x 75 mm were prepared and tested in this study. The first group included six unreinforced GPC specimens and was considered as the control group of specimens. The second group included six GPC specimens reinforced with one layer of geogrid. The third group included six GPC specimens reinforced with two layers of geogrid. The triaxial geogrid reinforcement was placed at a depth of 37.5 mm from the surface of the specimen. The tests were carried out by drying the GPC specimens in a controlled environmental chamber at a temperature of 27 ± 4°C and a relative humidity of 50 ± 10% for 98 days. It was found that the geogrid significantly reduced the thermal expansion and drying shrinkage of GPC specimens. The thermal expansion and drying shrinkage were less in the GPC specimens reinforced with two layers of geogrid compared to the GPC specimens reinforced with one layer of geogrid. It was also found that the rate of thermal expansion and drying shrinkage of the GPC specimens reinforced with geogrid was lower than that of the control unreinforced GPC specimens.

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Effect of Geogrid Reinforcement on the Drying Shrinkage and Thermal Expansion of Geopolymer Concrete

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ABSTRACT

The effect of triaxial geogrid reinforcement on the thermal expansion and drying shrinkage of geopolymer concrete (GPC) was experimentally investigated. Three groups of GPC prism specimens with a length of 280 mm and a cross-section of 75 mm × 75 mm were prepared and tested in this study. The first group included six unreinforced GPC specimens and was considered as the control group of specimens. The second group included six GPC specimens reinforced with one layer of geogrid. The third group included six GPC specimens reinforced with two layers of geogrid. The triaxial geogrid reinforcement was placed at a depth of 37.5 mm from the surface of the specimen. The tests were carried out by drying the GPC specimens in a controlled environmental chamber at a temperature of 27 ± 4° C and a relative humidity of 50 ± 10% for 98 days. It was found that the geogrid significantly reduced the thermal expansion and drying shrinkage of GPC specimens. The thermal expansion and drying shrinkage were less in the GPC specimens reinforced with two layers of geogrid compared to the GPC specimens reinforced with one layer of geogrid. It was also found that the rate of thermal expansion and drying shrinkage of the GPC specimens reinforced with geogrid was lower than that of the control unreinforced GPC specimens.

KEYWORDS: triaxial geogrid reinforcement; geopolymer concrete; drying shrinkage; thermal expansion.

1. INTRODUCTION

Concrete is the most versatile construction material used in the world. The Ordinary Portland Cement (OPC) is the primary material used in the production of concrete. The production of OPC is associated with the emission of carbon dioxide (CO_2) into the atmosphere. It was estimated that the production of OPC causes about 5 to 7% of the total CO_2 emissions worldwide.[1, 2] Hence, the use of industrial by-product materials has been investigated as viable alternative binders to OPC for reducing carbon dioxide (CO_2) emissions.[3, 4] Geopolymer Concrete (GPC) is a new type of concrete, which is produced by using industrial by-products such as fly ash (FA), ground granulated blast furnace slag (GGBFS), and silica fume (SF) replacing 100% of cement in the concrete. It was estimated that the geopolymer concrete (GPC) could reduce CO_2 emissions associated with the production of OPC by 26-45%.[5]

Geopolymer concrete is an aluminosilicate inorganic polymer, which is formed by polymerisation of aluminosilicate source with the presence of alkaline activator solutions such as sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH).[6] Due to the lower greenhouse gas emission compared to cement, high early strength, high fire resistance, high surface hardness and durability against chemical attack, GPC has the high potential to be used as a new construction material alternative to the OPC concrete.[7, 8]

The GPC is usually produced by using fly ash under heat curing conditions. Due to the heat curing of GPC, the applications of the GPC in the construction industry has been limited to the construction of precast concrete members. Therefore, the development of GPC at ambient curing conditions is very important for its wide applications in the construction industry.[9]

The water is not an essential ingredient in the production of GPC, unlike OPC concrete. Water is only used for producing a workable mixture for GPC.[10] At an early age, for the GPC produced with inadequate curing, excessive evaporation of the moisture conditions from the GPC may lead to a significant deterioration of GPC due to the thermal expansion or drying shrinkage.[11]

Some of the research studies investigated the addition of different types of fibers into the GPC mix to reduce the drying shrinkage of GPC.[12, 13] The inclusion of micro steel fibers into the GPC mix significantly reduced the drying shrinkage of the GPC.[14] However, to achieve a uniform consistency for the fiber reinforced GPC, the mixing of the GPC ingredients with steel fibers requires high energy before obtaining a suitable consistency for the GPC mixture. Also, using fibers as a shrinkage reducing material of the GPC may cause problems in the workability and flowability of fiber reinforced GPC, especially with a high percentage of fiber.

Geogrid is a polymeric structural material consisting of regular apertures such as square, rectangular and triangular openings.[15] The geogrid is mainly used for stabilizing weak soils to improve the stiffness of the foundations underneath road and railway structures.[16-18] The geogrid can be manufactured with three different processes including bonding, extruding polymers, knitting or weaving processes.[15, 19]

Various types of the geogrid were recently used as main confinement and reinforcement materials for OPC concrete elements. Meski and Chehab[18] studied the flexural behavior of concrete beams reinforced with geogrid. The test results showed that the geogrid reinforcement could increase the load capacity of the geogrid reinforced concrete beams. Siva Chidambaram and Agarwal[20, 21] and Shabana and Yalamesh[22] investigated the flexural behavior of steel fibers reinforced concrete beams confined with geogrid. The test results revealed that the geogrid significantly improved the strength and ductility of steel fibers reinforced concrete beams confined with the geogrid. It was also found that the geogrid confinement improved the post-yield behavior and increased the shear strength of the steel fibers reinforced concrete beams.[20-22] Chidambaram and Agarwal[23] and Wang et al[24] used the geogrid to confine concrete cylinders reinforced with steel fibers. The test results illustrated that the geogrid improved the axial stress-axial strain behavior of the concrete cylinders and could be used to confine the concrete.

Al-Hedad and Hadi[25, 26] investigated the effect of geogrid reinforcement on the flexural behavior of OPC concrete slabs. The geogrid reinforced concrete slabs were tested under static loads at three different locations: corner, edge and interior of the slab. The test results showed that the load capacity of OPC concrete slabs reinforced with the geogrid improved and the propagation of cracks were delayed considerably. Al-Hedad et al[27] and Al-Hedad and Hadi[28] used the geogrid as a shrinkage reducing material for normal strength concrete. The concrete prisms reinforced with geogrid dried under ambient conditions to measure the drying shrinkage. The results showed that the geogrid reduced the drying shrinkage strains of the concrete.

The demand for GPC has increased significantly in recent years especially for engineering applications such as highway pavements.[29] This study investigates the effect of geogrid on the thermal expansion and drying shrinkage of GPC cured under ambient conditions. Eighteen GPC prism specimens reinforced with geogrid were prepared and tested. All the GPC prism specimens were cured at a temperature of 27 ± 4˚ C and a relative humidity of 50 ± 10% for 98 days.

2. CHARACTERISTICS OF GEOGRID

The triaxial geogrid with triangular apertures was used in this study. The triaxial geogrid was manufactured by extruding process.[15, 19] As reported in Table 1, the apertures of the triaxial geogrid were equilateral triangular in shape and had a side length of 35 mm. The ribs of the triaxial geogrid were connected at the node to form the triangular aperture. The thickness and width of the ribs of the triaxial geogrid were 1.50 mm and 1.55 mm, respectively, which were measured at the mid-length of the ribs. The diameter and thickness of the node were 10 mm and 4 mm, respectively.

The tensile properties of the triaxial geogrid were determined according to the ASTM D6637/6637M-2015[30] and BS EN ISO-10319-2015.[31] In this study, the wide-width tensile tests for one and two layers of the triaxial geogrid were conducted. For one and two layers of the triaxial geogrid, the triaxial geogrid samples were tested in two orthogonal directions: machine direction (Samples MD and 2MD) and cross-machine direction (Samples CMD and 2CMD), as shown in Figure 1. In the machine direction of the triaxial geogrid, the transverse ribs of the triaxial geogrid are extended parallel on the width of the geogrid roll (Figure 1(a)). In the cross-machine direction of the triaxial geogrid, the transverse ribs of the triaxial geogrid are extended perpendicular on the width of the geogrid roll (Figure 1(b)).

Table 1 presents the properties of triaxial geogrid samples, which represented the average of the test results of five triaxial geogrid samples. The average widths of Samples MD and Samples CMD were 220 mm and 200 mm, respectively. The average widths of Samples 2MD and Samples 2CMD were 223 mm and 200 mm, respectively. The average gauge lengths of Samples MD, CMD, 2MD and 2CMD were 106 mm, 109 mm, 111 mm and 109 mm, respectively. The dimensions of the triaxial geogrid samples tested in this study satisfied the requirements of BS EN ISO 10319-2015.[31]

The tensile testing of the triaxial geogrid samples was carried out at a strain rate of 20% per minute in the laboratories of the School of Civil, Mining and Environmental Engineering at the University of Wollongong, Australia. The tensile testings were conducted using an Instron universal testing machine, Model 8033.[32]

The average ultimate loads of Samples MD and Samples CMD were 5.0 kN and 3.7 kN, respectively. The average ultimate loads of Samples 2MD and Samples 2CMD were 7.7 kN and 4.5 kN, respectively. The average elongations at the ultimate load of Samples MD and Samples CMD were 13.6% and 12.1%, respectively. The average elongations at the ultimate load of Samples 2MD and Samples 2CMD were 13.5% and 10.2%, respectively.

The secant moduli (kN/m/elongation%) at 5% elongation were determined. The average secant moduli of Samples MD and Samples CMD were 2.3 and 2.4 kN/m/elongation%, respectively (Table 1). The average secant moduli of Samples 2MD and Samples 2CMD were 4.2 and 3.8 kN/m/elongation%, respectively.

3. PREPARATION OF GPC

Ground granulated blast furnace slag (GGBFS) and Class F fly ash (FA) according to ASTM C618[33] were used as the main aluminosilicate materials for the production of the GPC. The GGBFS was obtained from the Australian Slag Association.[34] The FA was obtained from Eraring Power Station, Australia.[35] The chemical compositions of the GGBFS and FA were determined by X-Ray fluorescence (XRF) spectroscopy. The chemical composition analysis of GGBFS and FA was conducted in the School of Earth Science at the University of Wollongong, Australia. The chemical compositions of GGBFS and FA are presented in Table 2. Sodium hydroxide solution (NaOH) blended with sodium silicate solution (Na_2SiO_3) (Grade D) was used as an alkaline activator. The NaOH solution of 14 mole/ litre concentration was prepared by dissolving 97–98% pure pallets in potable water. The mass ratio of silicate (SiO_2) to sodium oxide (Na_2O) of the sodium silicate (Na_2SiO_3) solution was 2 with chemical compositions of 29.4% SiO2, 14.7% Na2O and 44.1% water.[36] The coarse aggregate with a maximum size of 10 mm and river sand as fine aggregate were used for preparing all GPC specimens. To enhance the workability, high range water reducer (Glenium 8700) was used.[36]

Table 3 provides details of the mix proportion of GPC adopted from a previous study by Hadi et al[36]. The GPC specimens were prepared by mixing the dry materials (GGBFS+FA, coarse aggregate, and fine aggregate) in a pan mixer for about 3 minutes. Afterwards, half of the amount of alkaline activator (combination Na_2SiO_3 with NaOH) was added slowly into the mixer and mixed for about 2 minutes. The remaining amount of the alkaline activator, superplasticizer and water were added to the mixer. The mixing continued for another 3 minutes until a homogeneous GPC mix was obtained. All GPC specimens were cast in three layers, and each layer was vibrated using a table vibrator for about 10 seconds to remove air bubbles.

The mechanical properties of GPC were determined at 28 days. Polyvinyl chloride (PVC) cylindrical molds of 100 mm diameter and 200 mm height were used for preparing GPC cylinders to determine the indirect tensile strengths of GPC according to AS 1012.10-2000.[37] In addition, plywood molds of 100 mm × 100 mm × 500 mm were used for preparing the GPC specimens to measure the flexural strength of GPC according to AS 1012.11-2000.[38] All GPC specimens were cured at the ambient condition until the day of testing (28 days). In addition, the compressive strength of GPC at 28 days was determined by testing three of 100 mm × 100 mm × 100 mm GPC cubes. The GPC cubes were cured under ambient conditions until the day of testing.

4. EXPERIMENTAL PROGRAM

4.1. Details of GPC specimens

Table 4 presents the details of the GPC prism specimens prepared to investigate the effect of the geogrid reinforcement on the drying shrinkage and thermal expansion of GPC. In this study, plywood molds of 75 mm × 75 mm × 280 mm were used for casting the GPC specimens to measure the drying shrinkage and thermal expansion according to AS 1012.8.4 (2015).[39] For each specimen, two gauge studs made of stainless steel with a length of 22.5 mm and a diameter of 6 mm were fixed at the ends of the longer side of the specimen. The specimens in this study were divided into three groups with six specimens in each group. The first group included unreinforced GPC specimens (Group UGPC) and considered as control specimens. The second group included six GPC specimens reinforced with one layer of geogrid (Group GGPC). The third group included six GPC specimens reinforced with two layers of geogrid (Group 2GGPC). The geogrid was located at 37.5 mm from the surface of the specimens (at the mid-depth of the GPC specimens), as shown in Figure 2.

All groups of the GPC specimens (Groups UGPC, GGPC and 2GGPC) were cast using plywood molds, as shown in Figure 3. The inside dimensions of plywood mold were 75 mm × 75 mm ×

280 mm. For the geogrid reinforced GPC specimens, the long sides of the plywood molds were made of two parts and each part had a height of 36.5 mm. The long sides of the plywood molds was fabricated in two parts to ensure correct placing the geogrid layers at the required level (37.5 mm). Two gauge studs made of stainless steel with a length of 22.5 mm and a diameter of 6 mm were tightened in the gauge stud holders at the ends of the plywood molds (Figs. 2 and 3). The tips of the gauge studs were considered as reference points during the measurements of the drying shrinkage and thermal expansion of the GPC specimens. The geogrid layers were fixed to the plywood molds using steel bolts (6 mm diameter and 106 mm long). The inside of the plywood molds was lubricated using some light oil to ensure an easy removal of the GPC specimens from the plywood molds.

After casting, the GPC specimens were kept in a cupboard with a temperature of 23 ± 3˚ C and a relative humidity of 92% for 24 hours. Afterwards, the GPC specimens were removed from the plywood molds and dried within the specified range of temperature and relative humidity during the entire drying period.

4.2. Testing of GPC specimens

The tests of thermal expansion and drying shrinkage of GPC started with drying the GPC specimens at a temperature of 27 ± 4˚ C and a relative humidity of 50 ± 10% for 98 days. The tests were carried out using a controlled environmental chamber with the dimensions of 850 mm × 950 mm × 2200 mm. The walls of the controlled environmental chamber were covered with a thick wool blanket to maintain the drying conditions of the controlled environmental chamber within the required level. The top of the controlled environmental chamber was covered with two glass doors to monitor the GPC specimens during the drying period.

The temperature of the controlled environmental chamber was maintained at the range of 27 ±

4˚ C during the entire drying period. An air heater (model TH-810T) was placed inside the controlled environmental chamber to control the temperature within the required range.[40] The air heater was connected with electric power through a digital thermostat plug. The digital thermostat plug was set up for the temperatures of 23 to 31˚ C. The air heater automatically operated when the temperature of the controlled environmental chamber was lower than 23˚ C until the temperature became more than 24˚ C. At a temperature greater than 31˚ C, the glass doors of the controlled environmental chamber were manually opened, and an extra fan was operated until the temperature became lower than 30˚ C.

The relative humidity of the controlled environmental chamber was maintained within 50 ± 10% during the drying period. Two dehumidifiers were used in the controlled environmental chamber.[41] The dehumidifiers were used during the whole drying period. A steel tray with a piece of hessian was also used in the controlled environmental chamber. The steel tray was filled with water during the entire drying period. According to the readings of the temperature and relative humidity, which were collected daily, except the weekends, public holidays and Christmas day, the temperature and relative humidity of the controlled environmental chamber were kept at 27 ± 4˚ C and 50 ± 10%, respectively.

4.3. Measurement and collection of data

The thermal expansion and drying shrinkage of the GPC specimens were calculated according to the procedure specified in AS 1012.8.4 (2015)[42]. All results of the thermal expansion and drying shrinkage represent the average test results of six GPC specimens. The thermal expansion and drying shrinkage of the GPC specimens were measured using a vertical length comparator device. The vertical length comparator device had a digital dial gauge with an accuracy of 0.001 mm.

The measurements of the thermal expansion and drying shrinkage of the GPC specimens were initially collected at the age of 1 day. The collected measurements at the age of 1 day of the GPC were considered as the initial length measurements of the GPC specimens. During the drying period, the measurements of the thermal expansion and drying shrinkage of the GPC specimens were continuously collected at every 7-day up to the age of 98 days. The thermal expansion and drying shrinkage of the GPC specimens were calculated by subtracting the measurements of the testing day (at every 7 days) from the initial length measurements (at the 1 day). The test results were divided by the effective gauge length. The effective gauge length is considered as the distance between the inner ends of the gauge stud, which were fixed at the ends of the GPC specimens. In this study, the effective gauge length was 250 mm.

5. TEST RESULTS

5.1. Mechanical properties of GPC

Table 5 presents the mechanical properties of GPC including flexural, indirect tensile and compressive strengths at 28 days. Three specimens were tested, and the average of flexural, indirect tensile and compressive strengths of the GPC are reported. The average flexural and indirect tensile strengths were 3.1 and 2.7 MPa, respectively. The average compressive strength obtained from testing the three GPC cubes was 35.6 MPa.

5.2. Effect of drying conditions on the behavior of GPC

During the drying period of the GPC specimens, the thermal expansion for the control GPC specimens (unreinforced) occurred. The significant thermal expansion of the control GPC specimens took place during the initial drying period from the age of 1 day to the age of 28 days. The GPC specimens reinforced with the geogrid significantly expanded at the early age of the drying period (at the age of 21 day to the age of 28 days). A noticeable reduction in the thermal expansion of the GPC specimens occurred at the age of 42 days to the end of the drying period (at the age of 98 days).

It can be mentioned that the control GPC specimens (unreinforced) expand during the entire drying period. The behavior of the GPC specimens reinforced with the one layer of geogrid fluctuated due to controlled drying conditions between the thermal expansion and drying shrinkage. Similar observations were reported in Yang et al.[43] and Melo et al.[44] for the geopolymer mortar. In this study, the thermal expansion of GPC specimens may have occurred because the specimens were kept at a high internal relative humidity in the moisture-curing stage. During the testing period, the internal relative humidity moved to the pores and voids at the surface of the GPC specimens. This transportation increased the internal moisture of GPC, which possibly led the GPC specimens to translate from the shrinkage to expansion behavior.

Within the environmental drying conditions (a temperature of 27 ± 4° C and a relative humidity of 50 ± 10%), the GPC specimens probably kept the internal relative humidity at a high level. Also, the geogrid layers possibly increased the percentage of pores and voids in the GPC specimens, in which the amount of confined water in the pores increased. As a result, the GPC specimens expanded during the drying period.

5.3. Thermal expansion and drying shrinkage of GPC

Figure 4 and Table 6 present average thermal expansion and drying shrinkage of the specimens of Groups UGPC, GGPC and 2GGPC with the age of GPC specimens. It can be seen that the average thermal expansion of the specimens of Groups GGPC and 2GGPC was lower than the average thermal expansions of the specimens of Group UGPC during the entire drying time. The average thermal expansion of the specimens of Group GGPC was lower than the average thermal expansion of the specimens of Group UGPC by about 58% at the age of 14 days and

12% at the age of 28 days. In addition, the reduction in the average thermal expansion of the specimens of Group GGPC was 56% at the age of 56 days, 66% at the age of 63 days in comparison with the average thermal expansion of the specimens of Group UGPC. The average thermal expansion of the specimens of Group GGPC was lower than the average thermal expansion of the specimens of Group UGPC by about 75% at the end of drying period (98 days). It can be concluded that the geogrid significantly influenced in reducing the thermal expansion of GPC reinforced with one layer of geogrid when subjected to ambient conditions.

Figure 4 also shows that the increase of the number of geogrid layers considerably reduces the thermal expansion of GPC. The average thermal expansion of the specimens of Group 2GGPC was lower than that of the average thermal expansion of the specimens of Group UGPC by about 61% at the age of 14 days and 15% at the age of 21 days (Figure 4 and Table 6). The average thermal expansion of the specimens of Group 2GGPC was 26% lower than the average thermal expansion of the specimens of Group UGPC at the age of 28 days.

Figure 4 shows test results of the average drying shrinkage of the specimens of Groups GGPC and 2GGPC. The average drying shrinkage of the specimens of Group UGPC was only observed at the age of 77 days. The average drying shrinkage of the specimens of Group 2GGPC was lower than the average drying shrinkage of the specimens of Group UGPC (control specimens) by about 14% at the age of 77 days (Figure 4 and Table 6). In comparison with the GPC specimens reinforced with the two layers of geogrid, the average drying shrinkage of the specimens of Group 2GGPC was much lower than the average drying shrinkage of the specimens of Group GGPC by about 38% at the age of 38 days and 47% at the age of 84 days (Figure 4 and Table 6).

The reduction of the thermal expansion and drying shrinkage of GPC specimens reinforced with geogrid was due to the role of the geogrid in resisting the thermal strains that occurred in the GPC specimens during the drying period. The role of the geogrid in resisting the thermal strains was directly dependent on the degree of the bond provided between the geogrid layer and the surrounding GPC. In addition, the test results illustrated that the increase in the number of the geogrid layers led to the reduction of the thermal expansion of GPC. As a result, when the GPC is subjected to the ambient conditions, the durability of the GPC can be improved over the service life.

5.4. Rate of thermal expansion and drying shrinkage of GPC

The rates of thermal expansion and drying shrinkage in mm/day of the GPC specimens of Groups UGPC, GGPC and 2GGPC are shown in Figure 5 and Table 6. The rates of thermal expansion and drying shrinkage of the GPC specimens were determined by dividing the thermal expansion of the GPC specimens of Groups GGPC and 2GGPC and the drying shrinkage of the GPC specimens of Group UGPC by the drying period. Figure 5 shows the average rates of thermal expansion and drying shrinkage of GPC specimens at different ages.

It can be seen from Figure 5 that the average rates of the thermal expansion or drying shrinkage of the specimens of Groups GGPC and 2GGPC were lower than that of the average rates of the specimens of Group UGPC during the entire drying period. The reduction of the average rates of the GPC specimens reinforced with geogrid was about 58% at the age of 14 days and 12% at the age of 28 days in comparison with the average rates of the control unreinforced GPC specimens (Figure 5 and Table 6). The average rates of the GPC specimens were lower than the average rates of the specimens of control unreinforced GPC specimens by about 56% at the age of 56 days and 98% at the age of 75 days (Figure 5 and Table 6).

The average rates of the thermal expansion and drying shrinkage of the GPC specimens reinforced with two layers of geogrid were lower than the average rates of the thermal expansion and drying shrinkage of the GPC specimens reinforced with the one layer of geogrid. The reduction of the average rates of the Specimens of Group 2GGPC was 15% at the age of 14 days, 96% at the age of 56 days and 69% at the age of 98 days in comparison with the average rates of the specimens of Group GGPC.

The reduction of the rates of formation of thermal expansion or drying shrinkage of the GPC specimens reinforced with the geogrid maintains the interlocking between the aggregates and the surrounding GPC paste. As a result, the durability of GPC structures is improved for a long time.

6. CONCLUSIONS

Eighteen geopolymer concrete (GPC) prism specimens reinforced with triaxial geogrid were tested to investigate the effect of geogrid reinforcement on the thermal expansion and drying shrinkage of geopolymer. The test results have led to the following conclusions.

1. The unreinforced GPC specimens sustained only the thermal expansion during the whole drying period. The GPC specimens reinforced with the geogrid sustained both thermal expansion and drying shrinkage.
2. The geogrid significantly decreased the thermal expansion of the GPC specimens reinforced with one layer of geogrid by about 12% at the age of 14 days and 66% at the end of the drying period (98 days) compared to the control unreinforced GPC specimens.
3. The GPC specimens reinforced with two layers of geogrid exhibited a considerable decrease in thermal expansion in comparison with the control unreinforced GPC specimens by about 61% at the age of 14 days and 26% at the age of 28 days.
4. During the whole drying period, the rates of formation of the thermal expansion and drying shrinkage of the GPC specimens reinforced with the geogrid was lower than that of the control unreinforced GPC specimens.

5. The thermal expansion and drying shrinkage of the GPC specimens reinforced with the geogrid can be significantly decreased with increasing the number of embedded geogrid layers.

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TABLE 1 Tensile properties of triaxial geogrid

Property, unit	**Results**
Material	Extruded triaxial geogrid
Inside dimensions of aperture (mm)	35 × 35 × 35
Thickness of rib (mm)	1.50
Width of rib (mm)	1.55
Diameter of nodal (mm)	10
Thickness of nodal (mm)	4

Property (unit)	One layer		Two layers	
	Samples MD(1)	Samples CMD(2)	Samples 2MD(3)	Samples 2CMD(4)
Width of test sample (mm)	220	200	223	200
Gauge length of sample (mm)	106	109	111	109
Ultimate load (kN)	5.0	3.7	7.7	4.5
Elongation at ultimate load (%)	13.6	12.1	13.5	10.2
Secant modulus at 5% elongation (kN/m/elongation %)	2.3	2.4	4.2	3.8

(1) and (2) :represent the results of tensile strength tests of one layer of triaxial geogrid samples tested in the machine and cross-machine directions, respectively.

(3) and (4) :represent the results of tensile strength tests of two layers of triaxial geogrid samples tested in the machine and cross-machine directions, respectively.

TABLE 2 Chemical compositions (mass %) of GGBFS and FA

Component	GGBFS	FA
Al_2O_3	14.96	27.5
SiO_2	32.40	62.2
CaO	40.70	2.27
Fe_2O_3	0.83	3.92
MgO	5.99	1.05
K_2O	0.29	1.24
Na2O	0.42	0.52
TiO_2	0.84	0.16
P_2O_5	0.38	0.30
Mn_2O_3	0.40	0.09
SO_3	2.74	0.08
LOI	NA	0.89

GGBFS: Ground Granulated blast furnace slag

FA: Flay ash

LOI: Loss on ignition

TABLE 3 Mix proportion of GPC (Hadi et al[36])

Geopolymer mix	**Quantity**
GGBFS (kg/m^3)	225
FA (kg/m^3)	225
Aggregate (10 mm maximum size) (kg/m^3)	1164
Sand (kg/m^3)	627
Alkaline activator/Binder	0.35
Na_2SiO_3/NaOH	2.5
Na_2SiO_3 (kg/m^3)	112.5
NaOH (kg/m^3)	45
NaOH (mole/liter)	14
Water (kg/m^3)	45
Superplasticizer (kg/m^3)	22.5

TABLE 4 Test matrix of GPC

Designation of group	Definition of group	Number of specimens	Label of specimens	Dimensions (mm)
UGPC	Unreinforced geopolymer concrete specimens	6	UGPC$_{1,\ 2,\ \ldots..,\ 6}$	75 × 75 × 280
GGPC	Geopolymer concrete specimens reinforced with one layer of geogrid	6	GGPC$_{1,\ 2,\ \ldots..,\ 6}$	
2GGPC	Geopolymer concrete specimens reinforced with two layers of geogrid	6	2GGPC$_{1,\ 2,\ \ldots..,\ 6}$	

TABLE 5 Mechanical properties of GPC

Property	Number of specimens	Average of dimensions of specimens, mm	GPC specimens			Average
			S1	S2	S3	
Flexural strength (MPa)	3	103 × 108 × 300	2.6	2.6	4.0	3.1
Indirect tensile strength (MPa)	3	100 × 200	2.8	2.7	2.6	2.7
Compressive stress (MPa)	3	100 × 100 × 100	36.5	35.0	35.2	35.6

S1, S2, and S3 represent the results of RPC specimens, which were tested to determine the mechanical properties of the RPC at the age of 28 days and cured at ambient conditions.

TABLE 6 Average thermal expansion and drying shrinkage of GPC specimens

Testing time (day)	**Group UGPC**		**Group GGPC**		**Group 2GGPC**	
	Average thermal expansion and drying shrinkage ($\times 10^{-6}$)	Average rate (mm/day)	Average thermal expansion and drying shrinkage ($\times 10^{-6}$)	Average rate (mm/day)	Average thermal expansion and drying shrinkage ($\times 10^{-6}$)	Average rate (mm/day)
7	218	0.0078	-1.3*	5.56E-05	-37.1*	0.0013
14	608.8	0.0217	254.1	0.0091	237.9	0.0085
21	921.7	0.0329	914.0	0.0326	797.5	0.0285
28	1005.2	0.0359	885.5	0.0316	748.9	0.0268
35	152.7	0.0055	-84.5*	0.0030	21.3	0.0008
42	117.6	0.0042	-194.3*	0.0069	-120.7*	0.0043
49	305.2	0.0109	24.1	0.0009	-36.7*	0.0013
56	154.8	0.0055	68.3	0.0024	-2.7*	9.52E-05
63	275.6	0.0098	95.1	0.0034	1.2	4.29E-05
70	114.4	0.0041	-3.1*	0.0001	-77.6*	0.0028
77	-114.8*	0.0041	51.2	0.0018	-99.1	0.0035
84	151.7	0.0054	-63.3*	0.0023	-33.5*	0.001
98	298.7	0.0053	75.5	0.0013	-23.1*	0.0004

* Drying shrinkage.