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Effect of geogrid reinforcement on the strains at compressive zone of concrete pavements

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Abstract

© 2020 fib. International Federation for Structural Concrete The current study investigated the effect of geogrid reinforcement on the fatigue behavior of concrete beam specimens in terms of the development of strains at the compressive zone. The concrete beam specimens having the dimensions of 150 mm × 150 mm × 550 mm were either unreinforced, reinforced with one layer of triaxial geogrid or reinforced with two layers of triaxial geogrid. The strains at the compressive zone of specimens were measured using strain gauges (SGs) fixed at two locations. The SGs of the first location were placed at the top of the specimens. The SGs of the second location were placed at 13 mm from the top of the specimens. The concrete beam specimens were tested under cyclic four-point bending loads with a frequency of 7 Hz. The cyclic four-point bending loads were carried out under a load control with a sinusoidal waveform for several stress levels. Test results indicated that triaxial geogrid reduced the average strains at the compressive zone by about 16% of the concrete beam specimens reinforced with one layer of geogrid and by about 25% of the concrete beam specimens reinforced with two layers of geogrid in comparison with unreinforced concrete beam specimens. The average rate of strain development at the compressive zone of geogrid reinforced concrete beam specimens was significantly lower than that of the unreinforced concrete beam specimens. In addition, the strains at the compressive zone of the concrete beam specimens reduced with increasing the number of geogrid layers.

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Effect of Geogrid Reinforcement on the Strains at Compressive Zone of Concrete Pavements

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ABSTRACT

The current study investigated the effect of geogrid reinforcement on the fatigue behavior of concrete beam specimens in terms of the development of strains at the compressive zone. The concrete beam specimens having the dimensions of 150 mm × 150 mm × 550 mm were either unreinforced, reinforced with one layer of triaxial geogrid or reinforced with two layers of triaxial geogrid. The strains at the compressive zone of specimens were measured using strain gauges fixed at two locations. The strain gauges of the first location were placed at the top of the specimens. The strain gauges of the second location were placed at 13 mm from the top of the specimens. The concrete beam specimens were tested under cyclic four-point bending loads with a frequency of 7 Hz. The cyclic four-point bending loads were carried out under a load control with a sinusoidal waveform for several stress levels. Test results indicated that triaxial geogrid reduced the average strains at the compressive zone by about 16% of the concrete beam specimens reinforced with one layer of geogrid and by about 25% of the concrete beam specimens reinforced with two layers of geogrid in comparison with unreinforced concrete beam specimens. The average rate of strain development at the compressive zone of geogrid reinforced concrete beam specimens was significantly lower than that of the unreinforced concrete beam specimens. In addition, the strains at the compressive zone of the concrete beam specimens reduced with increasing the number of geogrid layers.

KEYWORDS: triaxial geogrid; concrete pavements; cyclic loads; geosynthetic materials; bridges; strains; crack growth; concrete fatigue

1. INTRODUCTION

Concrete has excellent properties in compression. Concrete structures such as concrete pavements and deck slabs of bridges are designed to resist repeated loads. Repeated loads over the service life cause internal structural permanent changes resulting in fatigue damage of concrete structures.¹⁻⁷ These changes continuously grow from the tensile region (from the bottom of concrete pavements) to the compressive region (to the top of concrete pavements).

With the exposure of concrete pavements to repeated loads, the internal permanent changes develop to create microcracks. The microcracks gradually propagate and develop to macrocracks. As a result, the mechanical properties of concrete including compressive strength, load bearing capacity and the service life are reduced. The fatigue resistance of concrete pavements and deck slabs of bridges due to repeated loads also deteriorate.

Fatigue may also be the main reason for the failure of concrete pavements reinforced with steel bars or steel meshes. Over service time, the microcracks in the concrete pavements reinforced with steel bars or steel meshes propagate, thus allowing surface water to penetrate the concrete pavement through these microcracks. The functional role of steel bars or steel meshes in the concrete pavements declines due to corrosion. Flexural strength of steel reinforced concrete pavements deteriorates and, with not enough maintenance; the concrete pavements may be out service.

Geogrid is a geosynthetic material.^{8, 9} Geogrid is manufactured from propylene composite materials. It is used for stabilizing weak soils, landfill and subbase for the constructions of roads and railways.¹⁰⁻¹²

Different kinds of geogrid such as uniaxial, biaxial and triaxial geogrid have been recently tested as a reinforcement or confinement material for Portland cement concrete elements such as beams, slabs and cylinders.¹³ Meski and Shehab¹⁴, Shobana and Yalamesh¹⁵, Siva Chidabram and Agarwal¹⁶, Tang et al.¹⁷, and Ramakrishnan et al.¹⁸ investigated the flexural behavior of concrete beams reinforced or confined with geogrid. They reported that the geogrid reinforcement improved the mechanical properties such as flexural strength and tensile strength of concrete beams reinforced with geogrid. Siva Chidabram and Agarwal¹³ and Tang et al.¹⁷ also illustrated that geogrid reinforcement delayed the collapse failure of concrete beams. Al-

Hedad and Hadi¹⁹, Al-Hedad et al.²⁰ and Al-Hedad and Hadi²¹ illustrated that the load capacity and the drying shrinkage resistance of concrete slabs reinforced with triaxial geogrid increased. In addition, they reported that the propagation of cracks in the concrete slabs reinforced with geogrid took a long time before the cracks completely developed. In addition, Hadi and Al-Hedad²² have recently conducted an experimental study of fatigue performance of concrete specimens reinforced with geogrid. They illustrated that the fatigue performance including the loading capacity and resisting crack propagation of concrete specimens reinforced with geogrid are considerably improved. Siva Chidambaram and Agarwal²³ and Wang et al.²⁴ studied the effect of geogrid on the compressive strength of concrete cylinders. They reported that the compressive strength of concrete cylinders confined with geogrid increased. Al-Hedad et al.²⁵ reported the experimental results of the effect of geogrid materials on the thermal movements of the geopolymer concrete including the drying shrinkage and the thermal expansion under ambient conditions. They demonstrated that the geogrid could increase the resistance of geopolymer concrete reinforced with geogrid against the thermal movements.

As illustrated in the literature review, the applications of geogrid products in Portland cement concrete members are clearly increased. This study is a step in this direction. The current study investigates the influence of geogrid on the fatigue behavior of concrete beam specimens by investigating the development of strains at the compressive zone of the notched concrete beam specimens reinforced with geogrid.

2. EXPERIMENTAL PROGRAM

The experimental program included testing three groups of concrete beam specimens. The first group was unreinforced and taken as references. The second and third groups of concrete beam specimens were reinforced with one layer and two layers of geogrid, respectively.

2.1. Text Matrix

Table 2 lists details of test matrix that conducted in this study. Three groups of concrete beams specimens were tested. The dimensions of the concrete beam specimens were 150 mm × 150 mm × 550 mm. The first group, called Group UC, consisted of five unreinforced concrete beam specimens (Beams UC_{1,2,3,4,5}). The second group of concrete beam specimens were reinforced with one layer of geogrid and called Group GC, (Beams GC_{1,2,3,4,5}). The third group of concrete beam specimens, Group 2GC, were reinforced with two layers of geogrid and symbolled as Beams 2GC_{1,2,3,4,5} (Table 2). The triaxial geogrid was used as a reinforcing material and placed at a depth of 55 mm from the bottom of concrete beam specimens. A notch at the middle of the bottom of the concrete beam specimens was made. The width and length of the notch were 3 mm and 40 mm, respectively.

The concrete beam specimens used in this experimental study were prepared with normal strength concrete using Portland cement, Type general purpose, (169 kg/m³), coarse aggregate with a maximum size of 10 mm (820 kg/m³) and fine sand (332 kg/m³). The supplementary cementitious materials included fly ash (68 kg/m³) and ground granulated blast furnace slag (102 kg/m³) were used as a partial replacement of Portland cement. The water reducing admixture (1525 ml/m³), Type WRDA-PN20, was used in mixing the components of concrete mixture.²⁶ The water-reducing admixture was added to achieve the appropriate workability for the concrete mixture. The workability for the concrete mixture used for casting the concrete specimens reinforced with geogrid is very important. This is to ensure the flows of the concrete mixture through the openings of the geogrid layers. The ratio of water to binder was 0.45. The slump of fresh concrete mixture was 150 mm.

Plywood molds having internal dimensions of 150 mm × 150 mm × 550 mm were used in this study to cast the concrete of beam specimens. Five plywood molds for each group of the

concrete beam specimens (Groups UC, GC and 2GC) were fabricated, as shown in Figure 1. The level of triaxial geogrid reinforcement layer was located inside the plywood molds using a marker pen, Red in color. The steps that were followed in casting the concrete mixture of the specimens reinforced with triaxial geogrid were performed as follows. The first layer of concrete mixture was poured to a depth of 53 mm. The triaxial geogrid layer was placed at the required level with a slight pressure. The first layer of concrete mixture with the triaxial geogrid layer was compacted with a light vibration. The plywood molds were filled with the second layer of concrete mixture. The plywood molds including the concrete mixture and the triaxial geogrid layer were compacted using a table vibrator.²⁷ The placement of geogrid was checked after the test was completed for each tested specimen. The placement of geogrid was measured using a steel ruler. The measurements showed that all geogrids were located at the required level. A pointed concrete float made of steel was used for levelling the surface of the concrete mixture.

In order to determine the mechanical properties of the concrete, such as compressive strength and flexural strength, three cylinders of 100 mm diameter and 200 mm height, were cast and tested according to the requirements of AS 1012.9:20.²⁸ After one day of casting, concrete cylinders were taken out of the molds and cured in water with a standard temperature of $23 \pm 2^\circ$ C for 27 days. The average compressive strength of concrete at the age of 28 days was 40 MPa. The average flexural strength of concrete was determined according to the recommendations reported by Austroads²⁹ and found to be 4.7 MPa.

2.2 Properties of Triaxial Geogrid

Triaxial geogrid having the inside dimensions of 36 mm $\times$ 36 mm $\times$ 36 mm was used in this study, as shown in Figure 2. The ribs and nodes of the triaxial geogrid were manufactured from polypropylene composite materials.^{30, 31} The average thickness and width of the ribs of the

triaxial geogrid were 1.53 mm and 2.0 mm, respectively; which were measured at the middle of length of the rib. The average thickness and diameter of nodes of the triaxial geogrid were 3.5 mm and 10.5 mm, respectively.

Three samples in the machine direction and three samples in the cross-machine direction of the triaxial geogrid were prepared and tested in this study. This was done to determine the properties of the triaxial geogrid. As listed in Table 1, the average width and length of three samples of the triaxial geogrid tested in the machine direction were 255 mm and 127 mm, respectively. The average width and length of three samples of the triaxial geogrid tested in the cross-machine direction were 262 mm and 131 mm, respectively. The dimensions and the procedure of the tensile tests of the triaxial geogrid samples were performed according to the requirements of BS EN ISO 10319.³² The triaxial geogrid samples were tested under a strain rate of 20% per minute up to rupture.

Tensile tests of the triaxial geogrid samples were carried out using an Instron universal testing machine, Model 8033, having a capacity of 500 kN. The tensile tests of the triaxial geogrid samples were carried out at the laboratories of the School of Civil, Mining and Environmental Engineering at the University of Wollongong, Australia.

Tensile results of the triaxial geogrid samples are listed in Table 1. They showed that the average maximum load of triaxial geogrid samples tested in the machine direction was 6.9 kN and 5.1 kN for the triaxial geogrid samples tested in the cross-machine direction. The average strains at the maximum load of the triaxial geogrid samples tested in the machine and cross-machine directions were 14.2% and 10.6%, respectively.

The average secant modulus at 5% strain of the triaxial geogrid samples was 2.6% for the

triaxial geogrid samples tested in the machine direction and 2.5% for the triaxial geogrid samples tested in the cross-machine direction. The concrete beam specimens tested in this study were reinforced with placing the triaxial geogrid layer in the cross-machine direction.

2.3. Preparation of Strain Gauges

Four types of strain gauges were used in this study to measure the strains at the compressive zone of the concrete beam specimens. As listed in Table 3, they included Types PL-120-11, PFL-30-11, PFL-20-11 and BX120-5AA. These types of the strains gauges were supplied by Tokyo Sokki Kenyujo Company, Ltd.³³ The first type of strain gauges (Type PL-120-11) had a length of 120 mm with a gauge factor of $2.11 \pm 1\%$. The second type of strain gauges (Type PFL-30-11) had a length of 30 mm and a gauge factor of $2.08 \pm 1\%$. The third type (Type PFL-20-11) and the fourth type of strain gauges, Type BX120-5AA, had a length of 20 mm and 30 mm, respectively. The gauge factors of both the third and the fourth types of strain gauges were $2.08 \pm 1\%$.

The strain gauges were fixed at two locations of the concrete beam specimens (compressive zone), as shown in Figures 3 and 4. At the first location, the strain gauges were fixed at the top surface of the concrete beam specimens, called SG_{top} (Figures 3 and 4 (a)). The second location of the strain gauges was at 13 mm from the top of the concrete beam specimens, called SG₁₃ (Figures 3 and 4 (b)).

The preparation of location of the strain gauges was conducted according to the installation procedure reported by Catalog TML for standard strain gauges.³³ The positions of strain gauges, called bonding areas hereafter, were located at the top and at 13 mm from the top of the concrete beam specimens. The positions of strain gauges were marked using a marker pen and taken as a guide mark.

The bonding areas of strain gauges were cleaned using a brush and a cleaning tissue. The cleaning process of the bonding areas continued until the dust on the surface of the concrete was removed. An Araldite epoxy, Parts A and B, was used as an epoxy resin.³⁴ Parts A and B of the Araldite epoxy were mixed using a plate made of aluminum. Parts A and B mixture of the Araldite epoxy were spread equally and uniformly on the bonding areas. The bonding areas, which were covered by Parts A and B mixture of Araldite epoxy, was a larger than the area occupied by the strain gauges. The bonding areas with Parts A and B mixture of Araldite epoxy were left for 24 hours for the hardening purpose.

The strain gauges were bonded at the bonding areas of the concrete beam specimens using TML Strain Gauge Adhesive (Adhesive CN), Series CN, as an adhesive substance.³⁵ Adhesive CN was applied thinly and uniformly using an adhesive nozzle and spread over the back surface of strain gauges. The strain gauges with Adhesive CN were placed on the guide mark of the bonding areas of the concrete beam specimens with a light press down on the strain gauge for approximately 1 minute. Afterwards, the strain gauges were left for three days before starting the tests. The strain gauges were finally covered with an adhesive tape having a width of 18 mm. The adhesive tape was used to protect the strain gauges from scratching as that may occur when moving or setting up of the concrete beam specimens.

The strain gauges were checked before and after the installation procedure using a Multimeter device. The checking process of the strain gauges indicated that the strain gauges were correctly working.

3. TEST PROCEDURE

In this study, the specimens of Groups UC, GC and 2GC were tested under cyclic four-point bending loads with a frequency of 7 Hz. The concrete beam specimens were tested under cyclic

loading between the age of 150 days and the age of 350 days. The cyclic loading was applied with a sinusoidal waveform under various stress levels within a defined stress-range S^{min} to S^{max} up to failure, in which S^{min} and S^{max} represent the minimum and maximum cyclic loads, respectively. At the first stress level, the specimens of Groups UC, GC and 2GC were subjected to the maximum cyclic load equal to 12.5 kN. At the second stress level, the specimens were tested with a maximum cyclic load of 13.0 kN. Afterwards, the specimens were subjected to the maximum cyclic loads of 14, 15, 16, 17, 18, 19, and 20 kN. Some specimens of Groups UC, GC and 2GC failed before reaching the maximum cyclic loads of 18, 19 and 20 kN. The minimum cyclic loads (S^{min}) adopted in this test was equal to 15% of the maximum cyclic loads (S^{max}) for all stress levels. Wherefore, in regarding the development of strains at the compressive zone of the concrete beam specimens, the fatigue behavior of the concrete beam specimen reinforced with geogrid was investigated within the positive loading and unloading range.

The concrete beam specimens were subjected to 50000 cycles or more for each stress level. The total load cycles at failure applied for each specimen of Groups UC, GC and 2GC are listed in Table 3. During the testing, the strains at the compressive zone of the concrete beam specimens were measured simultaneously with applying the cyclic loads.

4. TEST RESULTS

The influence of triaxial geogrid on the fatigue behavior of concrete beam specimens in monitoring the strains measured at the compressive zone of the specimens reinforced with either one layer or two layers of triaxial geogrid were investigated. The strains at the compressive zone corresponding to the maximum cyclic load at the evaluated load cycle were measured and evaluated. Test results of concrete beam specimens reinforced with triaxial geogrid were compared with the test results of unreinforced concrete beams specimens.

4.1. Effect of Triaxial Geogrid on the Strains at Failure

The effect of triaxial geogrid on the strains measured at the compressive zone of Groups UC, GC and 2GC specimens at failure were evaluated, as shown in Figure 5. The strains at failure of Groups UC, GC, and 2GC specimens were determined according to the expression of $\{ST_{(fail)}^T = \sum_{j=1}^{j=SL} ST_{(fail)j}(S^{max}/S^{min})_j\}$, in which S^{min} and S^{max} represent the minimum and maximum cyclic loads, respectively; of stress at level j , $ST_{(fail)j}$ is the average strain at failure obtained from two or three test results of strains measured by SG_{top} (at the top of the specimen) and/or SG_{13} (at a distance of 13 mm from the top of specimen) strain gauges at stress level j , $ST_{(fail)}^T$ represents the total average strains measured at the compressive zone of each concrete beam specimen at failure, SL represents the total stress levels of concrete beam specimen up to failure.

It can be seen that the average strains at the compressive zone of Groups UC and GC specimens were close. While the average strains at the compressive zone of Group 2GC specimens were lower than the average strains at the compressive zone of both Groups UC and GC specimens. This illustrates that the triaxial geogrid with a single reinforcement layer did not have an impact in reducing the strains at the compressive zone of concrete beam specimens under cyclic loads. Using two reinforcement layers of geogrid reduced the strains at the compressive zone of Group 2GC specimens when subjected to cyclic loads.

The reduction of the average strains at failure for Group 2GC specimens was 8.5% lower than the average strains at the compressive zone of Group UC specimens. The average strains at failure of Group 2GC specimens were lower than the average strains at failure of Group GC specimens by about 10%.

The reduction of the average strains at failure at the compressive zone of the concrete beam

specimens reinforced with triaxial geogrid leads to prolonging the service life of the concrete pavements under traffic loads.

4.2. Effect of Triaxial Geogrid on the Strains-Maximum Cyclic Loads

The effect of triaxial geogrids on the strains measured at the compressive zone versus maximum cyclic loads of Groups UC, GC and 2GC specimens was evaluated. The strains shown in Figure 6 represent the average strains measured at the compressive zone of the Groups UC, GC and 2GC specimens for each stress level up to failure.

It can mention that the strains at the compressive zone of Groups GC and 2GC specimens were lower than the average strains at the compressive zone of Group UC specimens. This occurred at the maximum cyclic loads of 12.5, 13, 15 and 17 kN. While, the average strains at the compressive zone of Groups GC and 2GC specimens at the maximum cyclic loads of 14, and 16 kN were higher than those of Group UC specimens. At the maximum cyclic load of 13 kN, the average strains of Group 2GC specimens were higher than those of Groups UC and GC specimens.

In general, it can be said that the average strains measured at the compressive zone of the concrete beam specimens reinforced with one layer or two layers of triaxial geogrid reduced in the range of 2.0 to 3.3 times lower than the average strains at the compressive zone of unreinforced concrete beam specimens. As shown in Figure 6, the average strains measured at the compressive zone of specimens of Group UC (Beams_{1, 2, 3, 4, 5}) failed before reaching the maximum cyclic loads of 18, 19, and 20 kN.

4.3. Effect of Triaxial Geogrid on the Strains-Allowable Number of Load Cycles

The effect of triaxial geogrid on the strains measured at the compressive zone versus the allowable number of load cycles of Groups UC, GC and 2GC is shown in Figure 7. According

to the regime of cyclic loading tests that was followed in this study, the concrete beam specimens were subjected to 50000 cycles for each stress level up to failure (Table 3). The average strains at the compressive zone of Groups UC, GC, and 2GC specimens were determined by multiplying the average strains by the stress ratio for each stress level. The strains at the compressive zone, shown in Figure 7, represent the summation of the average strains at the number of load cycles 10, 20, 30, 40, and 50 cycles ($\times 1000$).

It is apparent that the total strains measured at the compressive zone were lower at the number of cycles of 10, 20 and 40 cycles ($\times 1000$) of Groups UC and GC specimens than the total strains of the specimens of Group 2GC. While the total strains measured at the compressive zone of Group 2GC specimens were lower at the number of cycles 50 cycles ($\times 1000$) than those of the Groups UC and GC specimens.

The results shown in Figure 7 indicate that the effect of triaxial geogrid on the strains measured at the compressive zone appeared at higher levels of load cycles for the concrete beam specimens reinforced with two layers of triaxial geogrid.

4.4. Effect of Triaxial Geogrids on the Development of Strains

The effect of triaxial geogrids on the development of strains at the compressive zone of Groups UC, GC, and 2GC was investigated, as shown in Figure 8. The rate of development of the strains at the compressive zone of Groups UC, GC, and 2GC specimens was calculated by determining the difference between the strains measured at the first stress level and the strains measured at the failure stress level (last stress level of each concrete beam specimen). The results of strains between the first and failure stress levels for each concrete beam specimen was divided by the duration of cyclic loading tests (sec). The average rate of strain development at the compressive zone, shown in Figure 8, represents the average rate of strain development

measured at the compressive zone during the complete cyclic loading test of Groups UC, GC, and 2GC specimens.

Test results indicate that the triaxial geogrid reinforcement succeeded in reducing the average rate of the development of strains at the compressive zone of Groups GC and 2GC specimens. The decrease of the average rate of strains at the compressive zone was by about 90% for Group GC specimens and 96% for Group 2GC specimens lower than the average rate of strains at the compressive zone of Group UC specimens. In addition, the number of geogrid layers exhibited a significant resistance of the development of strains at the compressive zone of Group 2GC specimens (reinforced with two layers of triaxial geogrid) by about 60% lower than those of Group GC specimens (reinforced with one layer of triaxial geogrid).

5. DISCUSSION

In this study, the effect of triaxial geogrid on the fatigue behavior of notched concrete beam specimens relative to the development of strains at the compressive zone of the concrete beam specimens was investigated. The concrete beam specimens were tested under cyclic four-point bending loads with various stress levels. At each stress level, the concrete beam specimens were subjected to 50000 cycles up to failure. At each applied cyclic load, tensile stresses and strains created at the tensile zone of the concrete beam specimens (below the neutral axis). Simultaneously, compressive stresses and strains were generated at the compressive zone of concrete beam specimens.

As proven in a previous study, the triaxial geogrid could reduce the tensile stresses and strains of concrete beam specimens tested under cyclic loads. Test results in this study indicate that the triaxial geogrid participated in resisting the cyclic loads and improved the compressive strength of concrete against the strains that were generated in the compressive zone of concrete beam

specimens plus the excellent compressive strength of concrete.

After many thousands of applied cyclic loads, microcracks in the concrete beam specimens initiated and distributed from the tension zone of the specimen towards the compressive zone. With existing cracks, the strain gauges fixed at the compression zone of the concrete beam specimens started recording the strains at the top of the compressive zone of the specimen. The strains increased with an increase of the applied cyclic loads together with the propagation of cracks. At this stage, the effect of geogrid on the development of strains at the compressive zone of the concrete beam specimen appeared. The test results obtained from this study illustrated that the geogrid exhibited a clear influence in reducing the strains created in the compressive zone. This may relate to the contribution of ribs of the geogrid embedded in the concrete in absorbing the pulsating loads which resulted from the applied cyclic loads. After many millions of applications of applied cyclic loads, microcracks rapidly propagated towards the compression zone of the concrete beam specimens. In general, the concrete beam specimens reinforced with geogrid exhibited a significant resistance against the development of strains at the compressive zone in comparison with the unreinforced concrete beam specimens. It can be mentioned that, with excellent compressive strength of concrete, the geogrid embedded in the tensile zone of the concrete beam specimens could succeed in reducing the strains at the compressive zone of the concrete beam specimens.

Reducing strains created at the compressive zone of the concrete structures reinforced with triaxial geogrid maintains the flexural behavior of the concrete structures against the fatigue damage for a long service time. In addition, the reduction of the strains at the compressive zone prolongs the fatigue life of the concrete structures before the failure took place. Increasing the number of triaxial geogrid layers exhibited a considerable effect in reducing the rate of development of the strains at the compressive zone of concrete specimens.

6. CONCLUSIONS

The effect of triaxial geogrid on the strains created at the compressive zone of the notched concrete beam specimens reinforced with either one layer or two layers of triaxial geogrid were studied. The test results of the strains at the compressive zone of the concrete beam specimens were compared with the test results of the strains of the unreinforced concrete beam specimens. In general, the concrete beam specimens reinforced with triaxial geogrid exhibited lower strains at the compressive zone in comparison with the unreinforced concrete beam specimens. The main conclusions obtained from the test results of this study can be drawn as follows:

1. The geogrid exhibited a clear influence in reducing the strains created at the compressive zone of the concrete beam specimens when cracks are initiated in the concrete and before failure took place.
2. Geogrid significantly reduced the average strains created at the compressive zone of the concrete beam specimens reinforced with either one layer or two layers of geogrid when subjected to cyclic loads.
3. The effect of geogrid in reducing the strains at the compressive zone of the concrete beam specimens was appeared at all stress levels for the concrete beam specimens reinforced with one layer of geogrid and at higher stress levels for the concrete beam specimens reinforced with two layers of geogrid.
4. The number of geogrid layers used as a flexural reinforcing material of the concrete pavements subjected to wheel loads had a considerable influence in reducing the strains at the compressive zone in the comparison with the concrete pavements reinforced with one layer of geogrid.

5. The reduction of strains at the compressive zone of concrete pavements results in improving the fatigue life and the serviceability conditions of the concrete pavements. In addition, the mitigation of strains generated at the compressive zone of concrete pavements reduces the costs required for the maintenance and the rehabilitation of concrete pavements.

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FIGURE 5 Total average failure strains at the compressive zone of Groups UC, GC and 2GC specimens

FIGURE 6 Average failure strains at the compressive zone versus maximum cyclic loads of Groups UC, GC and 2GC specimens

FIGURE 7 Average failure strains at the compressive zone versus the allowable number of load cycles for each stress level of Groups UC, GC and 2GC specimens

FIGURE 8 Average rate of strain development at the compressive zone of Groups UC, GC, and 2GC specimens

TABLE 1 Properties of triaxial geogrid

Properties of triaxial geogrid	Test results	
Inside dimensions (mm)	36 × 36 × 36	
Average thickness of ribs (mm)	1.53	
Average width of ribs (mm)	2.0	
Average thickness of nodes (mm)	3.5	
Average diameter of nodes (mm)	10.5	
	MD ^a	CMD ^b
Average width of three triaxial geogrid samples (mm)	255	262
Average length of three triaxial geogrid samples (mm)	127	131
Tensile results of three triaxial geogrid samples		
Average maximum load (kN)	6.9	5.1
Average strains at maximum load (%)	14.2	10.6
Average secant modulus at 5% strain (% strain)	2.6	2.5

^a and ^b: are the test results of triaxial geogrid samples tested in the machine and cross-machine direction, respectively.

TABLE 2 Text matrix

Groups	Number of specimens	Labels of specimens	Dimensions of specimens (mm)	State of reinforcement
Group UC	5	Beams UC _{1, 2, 3, 4, 5}	150 × 150 × 550	Unreinforced concrete specimens
Group GC	5	Beams GC _{1, 2, 3, 4, 5}	150 × 150 × 550	Reinforced with one layer of geogrid
Group 2GC	5	Beams 2GC _{1, 2, 3, 4, 5}	150 × 150 × 550	Reinforced with two layers of geogrid

TABLE 3 Strain gauges

Specimens	Number of strain gauges	Type of strain gauges	Gauge length ^a (mm)	Location of strain gauge	Number of cycles (× 1000)
Specimens of Group UC					
Beam UC ₁	2	PFL-30-11	30	13 mm location ^b	412
		PFL-30-11	30		
Beam UC ₂	2	PFL-30-11	30		59
		PL-120-11	120		
Beam UC ₃	2	PFL-20-11	20		136
		PFL-20-1	20		
Beam UC ₄	2	PL-120-11	120		356
		PL-120-11	120		
Beam UC ₅	3	PL-120-11	120	13 mm location	219
		PL-120-11	120	13 mm location	
		BX120-5AA	30	Top location ^c	
Specimens of Group GC					
Beam GC ₁	1	PL-120-11	120	13 mm location	708
		PL-60-11	60		
Beam GC ₂	2	PL-120-11	120	13 mm location	95
Beam GC ₃	2	PL-120-11	120	13 mm location	214
		PFL-30-11	30		
Beam GC ₄	3	PL-120-11	120	13mm-location	134
		PL-120-11	120	13mm-location	
		PL-60-11	60	Top location	
Beam GC ₅	3	PL-30-11	30	13 mm location	277
		PL-120-11	120	13 mm location	
		PL-60-11	60	Top location	
Specimens of Group 2GC					
Beam 2GC ₁	2	PL-120-11	120	13 mm location	373
		PL-60-11	60		
Beam 2GC ₂	2	PL-120-11	120	13 mm location	117
		PL-60-11	60		
Beam 2GC ₃	3	PL-120-11	120	13 mm location	416
		PL-120-11	120	13 mm location	
		PL-60-11	60	Top location	
Beam 2GC ₄	3	PL-120-11	120	13mm-location	275
		PL-120-11	120	13mm-location	
		PL-60-11	60	Top location	
Beam 2GC ₅	3	PL-30-11	30	13 mm location	217
		PL-120-11	120	13 mm location	
		PL-60-11	60	Top location	

^a represents the actual grid length in the sensitive direction of the strain gauge.

^b represents the location of strain gauges, which were placed at a distance of 13 mm from the top of the specimen.

^c represents the location of strain gauges, which were placed at the top of the specimen.