Flexural Behaviour of Concrete Beams Reinforced with Low or High-Ductility Geogrid

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Abstract. The deterioration of non-structural concrete elements in harsh environments is a major issue for Canada's cold regions. With conventional steel reinforcements being prone to corrosion and due to climate change-induced projected alteration in temperature, precipitation, and freeze-thaw patterns, the use of more durable reinforcing materials to avoid premature cracking in non-structural concrete components is desirable. In this paper, we investigate through mechanical testing the potential advantages of utilizing either low-ductility fibreglass grids with stiff polymeric coating or high-ductility polymeric geogrid as reinforcing layers to reduce crack opening and increase the flexural performance of plain concrete beams. A total of nine concrete beams with dimensions of 550×150×150 mm were thus prepared and tested under four-point bending, and their flexural behaviour was monitored in terms of load-deflection relationship, energy absorption capacity, and failure modes. Test results indicate that the use of stiff polymer coted fibreglass reinforcement can significantly improve the flexural capacity of plain concrete compared to their polymeric counterparts. Similarly, it was observed that fibreglass reinforcing solutions also provided superior resistance to cracking and post-cracking in comparison with control (plain) beams.

Keywords: Concrete Beam, Geogrid, Low-ductility Fibreglass Grids.

1. Introduction

Geosynthetics, including geogrids, have long been used in geotechnical engineering as reinforcement and stabilization materials [1]–[4]. Geogrids have recently been applied to reinforce weak subgrade soil for various ground-supported structures, such as pavements and slab-on-grade, to enhance their bearing capacity and limit their deflection [5]–[10]. However, there is still limited research on using geogrids for reinforcing non-structural concrete components exposed to harsh environments, where conventional steel often adversely impacts durability due to corrosion phenomena. This is particularly relevant for Canada, where climate change-induced swings in temperature, as well as alterations in precipitation and freeze-thaw cycles, are projected to increase dramatically [11]–[15]. Using geogrids as serviceability reinforcements for non-structural components in cold regions may represent an effective solution to address the impact of climate change on the built environment, as confirmed by previous pilot studies [16]–[19], whose potentialities albeit still remain largely unexplored.

In one study by Tang (2008), stiff and flexible biaxial geogrids were used to reinforce Portland cement concrete beams, with five specimens tested under four-point bending. Results showed that geogrids improved the post-cracking ductility and flexural strength of the concrete beams, with stiffer reinforcements performing better than flexible ones [20]. Other laboratory studies by El

Meski (2014) and Pavithra (2022) evaluated the mechanical contribution of geogrid reinforcements for concrete overlays using various configurations of uniaxial, biaxial, and triaxial geogrids. Both studies found that geogrid-reinforced concrete beams showed improved ductility, load and deflection flexural capacities compared to the unreinforced specimens [16], [21]. Al Masri Zaher Al (2018) compared the flexural behaviour of plain concrete beams against biaxial geogrid-reinforced specimens. The study used direct tension tests and 4-point flexural bending tests, also corroborated by Finite Element numerical simulations. Outcomes showed that reinforced beams had 130% higher load capacity and better post-cracking ductility, proving that geogrid solutions could be used to replace steel as reinforcement for ground concrete applications [22]. These results were echoed by those inferred by Itani (2016), who investigated the crack control performance of uniaxial geogrid reinforced concrete using direct tension tests and flexural bending tests. The results confirmed that uniaxial geogrid reinforced concrete had 25% higher tensile strength, better post-cracking ductility, and crack control performance compared to plain concrete [23].

For other test configurations, Al-Hedad Abbas (2019) and Rajesh Kumar (2021) conducted experiments to evaluate the impact of geogrid reinforcement on concrete slabs [24], [25]. Al-Hedad Abbas employed triaxial geogrid layers as reinforcement, while Rajesh Kumar compared the performance of steel and geogrid-reinforced concrete slabs. Both researchers found that using geogrid improved the flexural strength by at least 15% as well as improved the cracking resistance of concrete slabs [24], [25]. Moreover, Al-Hedad (2017) utilized 13 strain gauges to assess the surface strain of three control slabs and three slabs reinforced with a triaxial geogrid layer located approximately 17 mm from the bottom. Results concluded that geogrids significantly enhance the flexural strength of concrete slabs [26]. It is worth noting that the mechanical properties of the geogrids were found to play a crucial role in the performance of reinforced concrete, as concrete beams reinforced with stiff geogrids consistently achieved better results [16], [24]. Considering previous test results, this study investigates the mechanical contribution offered by stiff fibreglass geogrids as a new type of reinforcement for non-structural concrete, exploring the flexural performance of fibreglass-reinforced concrete beams through comparisons with plain concrete polymeric geogrid-reinforced specimens.

2. Testing program and materials

2.1. Portland Cement Concrete

The Portland cement concrete mix used for the nine concrete beams was prepared using type I Portland cement, ¼” coarse aggregate, ½” coarse aggregate and sand. Table 1 shows the mix design of the used concrete. The maximum size of the aggregate is smaller than the geogrid aperture dimensions to allow large aggregates to pass through them. Moreover, the concrete’s average slump of 120 mm allowed adequate contact and interlocking between aggregate and geogrids. The resulting concrete was poured into moulds and allowed to cure for 28 days before testing. In addition, eight concrete cylinders were tested for compressive and tensile split tests. The nominal compressive and tensile strengths were found to be 35MPa and 4MPa, respectively.

Table 1: Mix proportion.

W/C	Water (kg)	Cement (kg)	1/4" Coarse aggregate (kg)	1/2" Coarse aggregate (kg)	Sand (kg)
0.55	40.5	73.62	118.8	43.56	139.86

***W/C is the ratio of the amount of water to the amount of cement used**

2.2. Geogrid

Two types of biaxial geogrid were used in this study. The first is a ductile polymeric polypropylene geogrid, and the second is a low-ductility fibreglass geogrid. The properties of each geogrid material were inferred from the recent studies from Desbrousses et al. (2021) and Shokr et al. (2021) and are shown in figure 1 [9, 26]. At room temperature (23°C), the polymeric geogrid has an ultimate tensile strength of 33 kN/m and ultimate strain of 14%, while the fiberglass geogrid has ultimate tensile strength and ultimate strain of 105 kN/m and 2%, respectively. Every sample used in this study was taken from the same roll of each material.

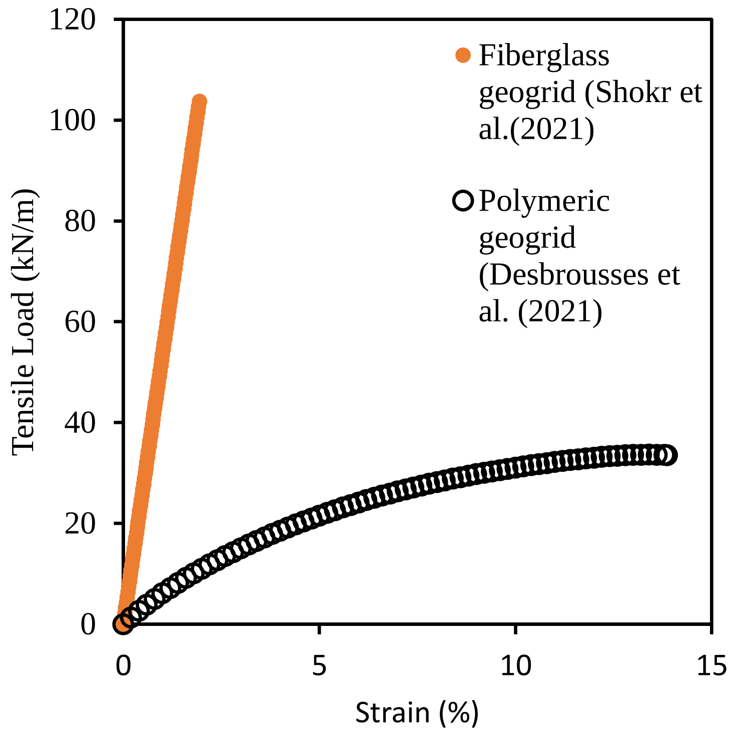

Fig. 1. Tensile Load-Strain Curve of two used geogrid adopted from Shokr et al. (2021) and Desbrousses et al. (2021)

2.3. Specimen Fabrication

Nine wooden moulds, measuring 55×15×15 cm, were prepared and filled with a 5 cm thick layer of concrete, as shown in figure 2a. The consolidation of the concrete and the creation of a uniform surface was facilitated by using a vibration table. For both tested reinforced materials, a 55×15 cm geogrid sheet was precisely placed on top of the initial layer of concrete at the bottom of the beam (figure 2 b). Subsequently, the second concrete batch was poured, and the surface was finished neatly (figure 2 c). To form the notch, a rectangular cross-section of glass, with a width of 150 mm and a depth of 15 mm, was bonded to the bottom of the mould at its midpoint.

Fig. 2. Casting process for concrete specimens: a) prepare the wooden mould, b) place the geogrid layer, c) surface finishing.

The concrete for nine specimens was mixed in three batches using a 0.1 m^3 concrete mixer. In order to minimize variability between the three batches, each specimen was cast from a single concrete batch. Furthermore, a set of three concrete cylinders were produced for each batch to test the concrete strength and gauge overall variability. The specimens and concrete cylinders were evaluated, and the results for compressive and tensile split tests indicated that the batch-to-batch variability was negligible.

2.4. Testing Setup and Measurement Instrumentation

The concrete specimens were subjected to flexural testing by applying a monotonic vertical loading at the beam mid-span using an MTS machine with a 150 kN load cell, as shown in figure 3. The monotonic load was applied in displacement control mode with a crosshead rate of 1.2 mm/min. Before each test, a steel ruler was attached to the mid-span of the top of the beam. This setup allowed for two linear variable differential transformers (LVDTs) to be placed at either end to measure the mid-span displacement, as illustrated in Figure 3. The four-point bending test was conducted using data acquisition software (Testworks), which collected data on both the applied loads and vertical mid-span displacements until failure was reached.

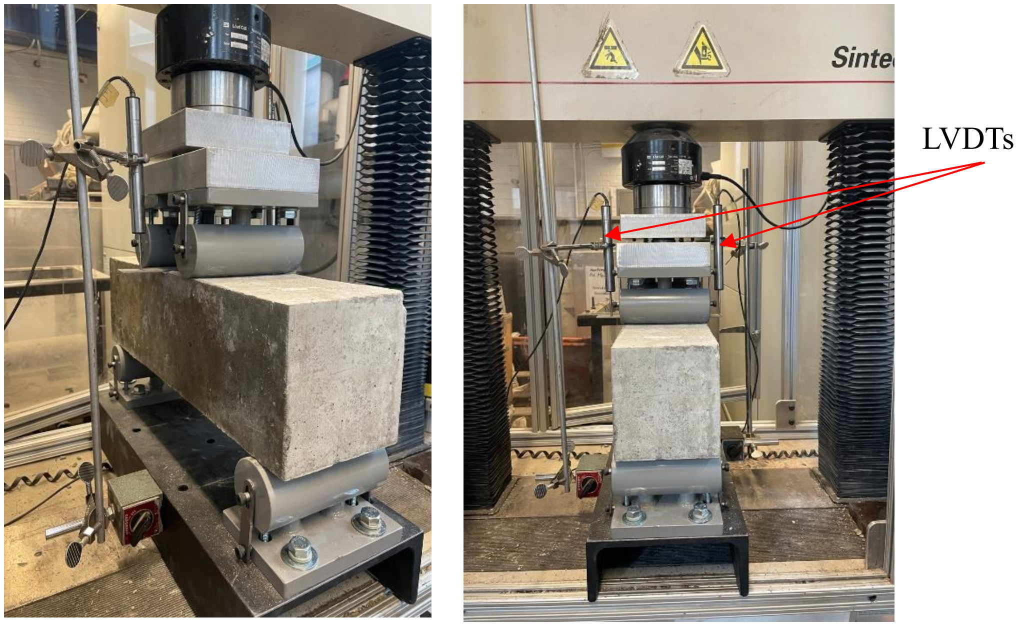

Fig. 3. 4-points flexural test setup

3. Experimental result and discussion

3.1. Test Result

In this section, an overview of test results is given by presenting representative outcomes for three control beams, three fibreglass geogrid-reinforced beams and three polymeric-geogrid reinforced beams. The vertical load vs mid-span displacement plots for control (plain) and reinforced concrete beams are shown in Figure 4. The control beams fail in a brittle manner with an average peak load of 13 kN, leading to a sudden drop in the load and separation of the beam into two parts, as seen in Figure 4. This is due to the brittle failure of concrete in the absence of any flexural reinforcement. For beams reinforced with polymeric geogrid, the peak load remained similar to that of the control beams; however, the load was redistributed to the geogrid after reaching the load peak point as the concrete layer could not handle further tensile stress. Once the stress in the geogrid reached the strength of one or more ribs, the load-deformation curve showed a sudden drop due to rib tear, and the load was carried mainly by the geogrid until the total failure of the beam. Beams reinforced with polymeric geogrid showed post-crack behaviour until the maximum mid-span deflection reached 18 mm. Beams reinforced with fibreglass geogrid showed similar post-crack behaviour at higher loads, with a 40% increase in peak load compared to plain and polymeric-reinforced beams. The fibreglass geogrid improved the load capacity of the concrete beams due to its relatively high strength and low ductility. The equation below was used to calculate the modulus of rupture for each specimen (ASTM 2015) [27].

$$R = \frac{Pl}{bd^2} \tag{1}$$

Where R is the modulus of rupture in MPa, P is the maximum applied load by the testing machine in N, l is the span length in mm, and b and d are the average width and depth of the specimen in mm, respectively. According to the average of three replicates specimens per set, specimens reinforced with fibreglass geogrid have been shown to increase their flexural strength by 25%.

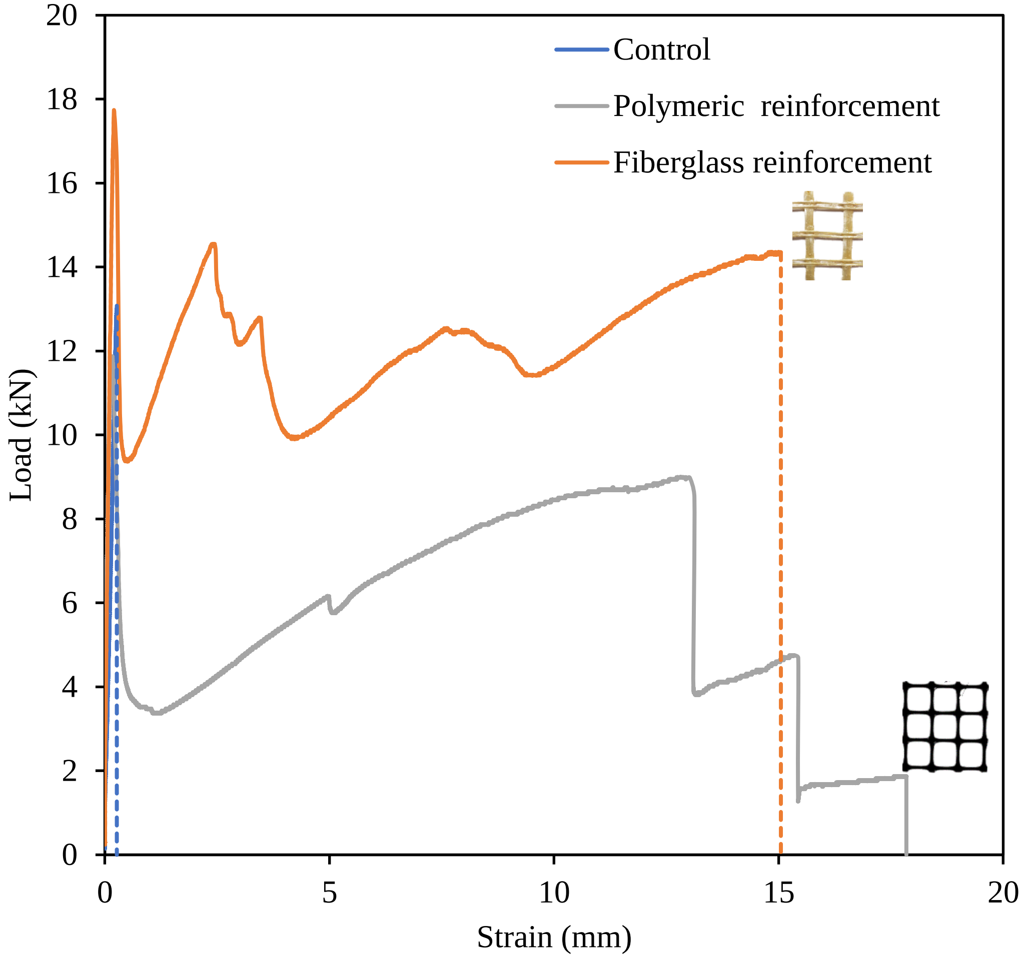

Fig. 4. Load versus deflection for the three replicate control beams, polymeric reinforced beams and fibreglass reinforced beams

3.2. Fracture Energy

The fracture energy of concrete beams is a key parameter that is determined by calculating the area under the load-deflection curve. Using two different types of geogrid reinforcement in concrete beams leads to an improvement in fracture energy, as demonstrated in Figure 4. Specimens reinforced with fibreglass geogrid demonstrated a 40% increase in fracture energy compared to those reinforced with polymeric geogrid. This increase is attributed to the higher strength and lower ductility of fibreglass geogrid compared to polymeric geogrid.

3.3. Failure Mode

Figures 5a -5c illustrate the different failure modes observed at every specimen configuration. When the control beams were tested, they failed in a brittle manner as they lacked any reinforcement, as demonstrated in Figure 5a. In contrast, the polymeric and fibreglass reinforced specimens exhibited ductile behavior, where the concrete and geogrid collaborated to absorb the bending-induced tensile stresses. Unlike plain and reinforced with polymeric geogrid cases, fibreglass geogrid reinforcement was able to maintain the beam integrity after the total failure was achieved, where the crack reached all the way to the top of the beams, as shown in Figure 4 c.

a) Control b) Polymeric geogrid reinforcement c) Fiberglass geogrid reinforcement

Fig. 5. Failure modes a) The control beams experienced immediate brittle failure leading to beam separation into two parts b) and c) delayed failure due to the geogrid action reinforcements c) fibreglass geogrid maintained the integrity of the beam even after a crack had reached the top of the beam.

4. Conclusions

This study presents an experimental investigation of the flexural behaviour of concrete beams reinforced with low or high-ductility geogrids. A total of nine concrete beams were prepared and tested under four-point bending. The results of beam flexure tests indicate that the use of geogrid as reinforcement for concrete beams provides several benefits. Both tested types of geogrid reinforcement provide ductile post-cracking behaviour, larger deflection, and higher fracture energy. Moreover, fibreglass geogrid reinforcement provides 25% higher flexural strength in comparison with control beams. It is important to note that the geogrid's physical and mechanical properties significantly impact the performance of reinforced beams in flexure. Fibreglass geogrid outperforms polymeric geogrid in terms of tensile strength with seven times lower ultimate strain. This results in a 40% increase in fracture energy of specimens reinforced with fibreglass geogrid compared to those reinforced with polymeric geogrid. Based on the preliminary results presented etc.

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