CSCE Annual Conference
Growing with youth – Croître avec les jeunes

Laval (Greater Montreal)
June 12 - 15, 2019

POTENTIAL ADVANTAGES OF BASALT FRP COMPARED TO CARBON FRP & CONVENTIONAL STEEL

Zaki, Mariam[1], Tobaa, Amira[2], Shehata, Ahmed[3], Mohamed, Farid[4], Khalef, Ramy[5] and Hagras, Yomna[6] , Abou Ali, Reem[7], Farag, Mayer[8], Ghaly, Athnasious[9], Madi, Magdi[10], Sayed-Ahmed, Ezzeldin[11], Abou-Zeid, Mohamed[12]
[1,2,3,4,5,6,7,8,9,10,11,12] The American University in Cairo, Egypt
[1] mariamyaza@aucegypt.edu

Abstract: In this study, an attempt was taken to evaluate the performance of basalt FRP bars compared with carbon FRP bars and conventional steel bars as a concrete reinforcement. Specimens of reinforced concrete were casted to fulfil this comparison. The casted beams comprised a common top reinforcement, stirrups spacing, and concrete properties. The difference was in the bottom reinforcement where it was once steel, Carbon FRP, Basalt FRP, and a hybrid of Basalt FRP and steel. These beams were tested for their behaviour under a flexural load through a four-point bending test. The remaining specimens were casted as columns with common stirrups spacing, and concrete properties. The behaviour of Basalt FRP, Carbon FRP, and steel reinforcement was tested upon the application of an axial compressive load. The bonding strength between concrete and the different candidate bars was tested through the bond pull-out test. Furthermore, tests were conducted on the thermal, chemical, and mechanical properties of the individual bars. This study was expected to yield an Evaluation of the main characteristics of the newly developed Basalt FRP bars and an Identification of the key differences and limitations of using BFRP in concrete structures in relation to CRFP and traditional steel reinforcement of concrete structure. Results showed an increase in the ultimate stresses carried by both FRP bars over conventional steel bars along with a decrease in ductility. Most importantly both FRP bars showed resistance to deterioration upon exposure to acid and alkali environments.

1.0 Introduction

The successful incorporation of conventional steel as a reinforcement of concrete has been dominant over the past decades. However, steel corrosion represents a major threat in the construction industry. Therefore, FRP (Fibre Reinforced Polymers) composites used as a concrete reinforcement are becoming more effective. In addition to FRP composites being leading icons in their characteristic strength to weight ratio, they also eliminate structure durability problems and increase its service life. FRP systems exist as composites of a polymer matrix and a fibre. The matrix through which the stress is transferred to the fibres exists to bind the fibres and add protection from surface damage. This fibre could be either glass, aramid, carbon, or basalt. There are numerous concerns regarding the use of glass, aramid, and carbon FRP with respect to the composite or its cost. However, the basalt FRP has been introduced but little research has been conducted to understand how it complements the advantages of an FRP system at a relatively low cost. Basalt is a volcanic igneous rock that is the most abundant rock type in earth's crust. Basaltic materials have a significantly high performance in terms of strength, corrosion resistance, temperature range, thermal stability, resistance to acids, resistance to the alkalinity of concrete, and finally their lower cost grants them a high potential to replace glass FRP, carbon FRP, and conventional steel. The formation of continuous basalt fibres was initiated in 1984 and was found to require less energy, than that required for glass or carbon fibres. (Nasvik, 2016) Hence basalt fibres are environmentally safer than alternative FRP composites. Studies have shown that when compared to carbon FRP, basalt FRP has a wider temperature range, higher compressive and shear strength. While carbon FRP has a higher tensile strength and elastic modulus. (Prince, 2011). This is due to the difference in molecular composition of carbon and basalt fibres, where carbon fibres are made of carbon atoms bonded in hexagon sheets that are folded randomly in the longitudinal direction preventing the folds from sliding past each other therefore, granting carbon fibres a high tensile strength. (Prince, 2011). The cost of the raw bars obtained from online suppliers indicates that Carbon FRP has the highest cost and steel has the lowest however this comparison is invalid due to different material capacities. If cost effectiveness is considered in terms of energy absorbed by beams, using steel remains more cost effective than Carbon FRP, however if the repair aspect of steel reinforced concrete structures is considered, according to a case study (Mackechnie 2001, Alexander 2001), a steel reinforced concrete structure of a 30 mm cover repaired at 10 year intervals has an estimated total life cycle cost of structure that is double the initial cost, therefore the carbon FRP reinforced beam becomes more cost effective. When considering the amount of energy absorbed by columns the Basalt FRP becomes more cost effective than steel reinforced concrete columns, hence upon repair of steel reinforced columns the cost effectiveness of basalt FRP reinforced columns is further magnified. The aim of this study is to determine which candidate reinforcement is best to be used in different reinforced concrete members. This work is expected to yield a better understanding of the properties offered by FRP, assess the potential advantages and disadvantages, and determine its cost effectiveness in an attempt to reach a more economic utilization of this fibre that can help designers in making more educated selections when used in concrete works.

2.0 Objectives and Scope

The objective of this study is to evaluate the potential advantages of basalt FRP when compared to carbon FRP and conventional steel. Multiple criteria will be used to perform the evaluation, as it will consider physical, mechanical, structural, chemical, environmental, and economical. Some of these criteria will be met through conducted experimental work, while the remaining will be attained through the literature review.

3.0 Experimental Program

3.1 Material Properties

- **Steel bars (diameters available in 12 mm; beams bottom reinforcement and columns reinforcement, 10 mm; beams top reinforcement and columns reinforcement, 8mm; stirrups)**
- **Carbon FRP bars (diameters available in 12 mm; beams bottom reinforcement and columns reinforcement)**
- **Basalt FRP bars (diameters available in 12 mm; beams bottom reinforcement, 10 mm; columns reinforcement)**
- **Concrete:**
    - **Fine Aggregates:** Normal Sand with a specific gravity 2.6.
    - **Coarse Aggregates:** Well Graded Dolomite with a specific gravity of 2.8. (MNA 38 mm)
    - **Water:** ordinary tap water used in concrete mix and curing.
    - **Admixture:** Superplasticizer.
    - **Cement**

3.2 Concrete Mix Design

The concrete mix used for all casted specimens was assumed to have an incidental air content of 2% and a water-to-cement ratio of 0.35, a superplasticizer was added to improve the workability at a 0.75% by weight of cement content.

Table 1: Concrete Mix Design

Item	
Cement	450 kg/m^3
Water	157.5 kg/m^3
Fine Aggregates	659 kg/m^3

Coarse Aggregates	1186 kg/m^3
Slump	70 mm
w/c ratio	0.35
28-day Compressive Strength	45 (+/-) 5 MPa

3.3 Tests

The testing was divided into four categories:

3.3.1 Tests on Fresh Concrete: a slump test was conducted to determine the workability of the poured mix.

3.3.2 Tests on Hardened Concrete: 7-day compressive strength and 28-day compressive strength tests were conducted each on 3 cubes respectively. The dimensions of the compressive strength cubes were (0.15 m x 0.15 m x 0.15 m).

3.3.3 Tests on Individual Reinforcement Bars

- **Unit Weight Test:** The volume of individual bars and their corresponding weights were measured to obtain the unit weight of the bar. This was performed on 3 specimens from each candidate reinforcement with a 12 mm diameter.
- **Water Absorption:** The bar was weighed then immersed in water for 24 hours, surface dried then re-weighed to obtain the amount of water it absorbed. This was performed on 3 specimens from each candidate reinforcement of length 20 cm and diameter of 12 mm.
- **Chemical Durability (Alkali Resistance):** The initial weight and volume of the specimens were recorded, then the specimens were exposed to 1 M concentration of NaOH solution for 14 days, then their weight and volume were re-measured after their exposure and any changes were recorded. This was performed on 3 specimens from each candidate reinforcement of length 3 cm and diameter of 12 mm.
- **Chemical Durability (Acidity Resistance):** The initial weight and volume of the specimens were recorded, then the specimens were exposed to 1 M concentration of H_2SO_4 solution for 14 days, then their weight and volume were re-measured after their exposure and any changes were recorded. This was performed on 3 specimens from each candidate reinforcement of length 3 cm and diameter of 12 mm.
- **Thermal Stability:** The bars were placed in an oven at a temperature of 100°C for 2 hours, then their tensile strength was measured and compared with tensile strength properties before heating. This is performed on 2 specimens from each candidate reinforcement of gauge length of 12 cm and a diameter of 12 mm

3.3.4 Tests on Hardened Concrete Reinforced with candidate bars

- **Bond Pull-out Test:** a total of 6 cylinders of concrete reinforced with one central bar (2 of each candidate reinforcement) are casted of a 30 cm height and 15cm diameter. The bar is protruding from one side of the cylinder in order to be pulled out with an embedded length equal to the height of cylinder (30 cm). In addition to that, the FRP bars will be embedded in a steel casing through an epoxy mortar in order to prevent slippage from the grip of the pulling machine. The strain rate was 0.2 mm/min.

- **Beams:** a total of eight beams were tested with the main objective of comparing the BFRP and CFRP reinforced beams with the concrete beams reinforced with the conventional steel bars with regard to strength, ductility, and deflection. The eight beams include two CFRP reinforced beams, two BFRP reinforced beams, two steel reinforced beams, and two hybrid beams. The hybrid beam configuration consisted of a bottom reinforcement of one bar of steel and one bar of basalt FRP. All the bars in the bottom reinforcement were diameter 12 mm, the remaining parameters were kept constant in order to allow the comparison to be valid. The parameters that were kept constant include the top reinforcement of the beams which consisted of 2 steel bars of a 10 mm diameter, the stirrups which consisted of steel of 8 mm diameter at a spacing of 100 mm along the beam, the reinforcement ratio, the concrete used which followed the mix design described in table 1, and the beam dimensions which were (0.15 m x 0.15 m x 1 m). The beams were subjected to a four-point bending test at a testing span of 0.75 m between the

2 supports. In addition to that, strain gauges were attached to measure the strain in the bottom reinforcing bars.

- **Columns:** a total of 6 columns were tested to observe the behaviour of columns reinforced with basalt FRP bars and carbon FRP bars in comparison to conventional steel reinforced columns. The columns were divided in to 2 categories, first of which is the 12 mm diameter category and the second is the 10 mm diameter category. Each category had a control column which was steel reinforced. The 12 mm category consisted of 2 (12 mm diameter) carbon FRP reinforced columns, while the 10 mm category consisted of 2 (10 mm diameter) basalt FRP reinforced columns. All columns had the same dimensions which were (0.75 m x 0.15 m x 0.15 m). the same reinforcement ratio was used in all columns (4 reinforcement bars), in addition to that the stirrups which consisted of steel of 8 mm diameter at a spacing of 100 mm along the column. This dense confinement provided by the stirrups is used as safety measure taken for the columns to reduce the catastrophic failure of the columns reinforced with the FRP material as their predicted mode of failure is brittle. Further confinement was added through U-shaped stirrups that form a column top and bottom cap to reduce the stresses that might cause failure at these points and create misleading results. Moreover, strain gauges were attached to the bars at the bottom 1/3 of the column height to measure the strain in the bars at a critical region under the compressive load.

4.0 Results and Discussion

4.1 Tests on Individual Reinforcement Bars Results

4.1.1 Unit Weight

Unit Weight tests were conducted on basalt, carbon, and steel rods. Basalt and Carbon FRP rods unit weights were comparable. The Basalt rod recorded a value of 2348 kg/m^3, and the Carbon rod recorded a value of 1842 kg/m^3. On the other hand, the Steel recorded a value three to four times the value of the FRPs, it had a unit weight of 7636 kg/m^3.

4.1.2 Water Absorption

The specimens proved to be impermeable to water as they showed stability in weight and volume upon the 24 hours in water.

4.1.3 Chemical Durability (Alkali Resistance)

All the three specimens showed no change in their physical properties or their appearance, there was no degradation in their surfaces, and they did not lose weight nor volume. This test can prove that the three specimens can sustain the alkalinity of the cement inside the concrete.

4.1.4 Chemical Durability (Acidity Resistance)

The Carbon FRP and Basalt FRP have not experienced any change in their physical properties and this was proven by their stability in weight and volume. However, the steel specimen has been affected by the acid through surface degradation, corrosion, and hence loss in weight.

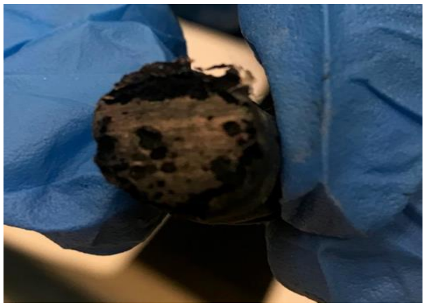

Figure 1: Surface degradation of steel specimen

4.1.5 Thermal Stability

4.1.5.1 Initial Attempt Keeping Bars at 600°C for 2 hours

This temperature was selected as a representable one according to the literature review which indicated that all three candidate bars can maintain their properties up to 800°C, which after experimentation the carbon FRP bars proved to disintegrate completely from the matrix. While the epoxy in the basalt FRP bars' matrix expanded leaving air voids inside the bar and making it more brittle. No physical damage occurred to the steel bars.

Figure 2: Carbon FRP bars after 2 hours at 600°C

Figure 3: Basalt FRP before (left) and after (right) heating

4.1.5.2 Corrected Attempt Keeping Bars at 100°C for 2 hours

This temperature was selected upon checking the thermal stability technically specified by the suppliers of the bars. Where the Basalt FRP bars were designed to sustain their properties up to 300°C, while the Carbon FRP bars were designed to sustain their properties up to 150°C. Therefore, a temperature of 100°C was chosen to be representable as to determine whether the bars lose strength upon exposure to high temperature. After being kept at 100°C for 2 hours and then left to cool for an appropriate time. All three bars exhibited no change in their physical properties. Then the tensile strength test was conducted upon them where the steel bar was found to lose 6% of its ultimate tensile strength while the Basalt FRP lost 10%. The carbon FRP specimens failed due to slippage within the material as described in section 4.3.2 of this report.

Figure 4: From Left to Right (Steel, Carbon FRP, Basalt FRP) after heating

4.2 Tests on Hardened Concrete Reinforced with Candidate Bars Results

4.2.1 Bond Test

The steel specimen showed a ductile failure in the bar at 70 KN. For the carbon FRP, there was a crack along the centerline of the cylinder where failure occurred at 87 kN. Finally, the Basalt FRP showed a crack along the center line however it did not fail along it, rather it failed due to a crack in the upper third of the cylinder that initiated due to a weak point that was created supposedly because of excess water or concrete bleeding. It failed at 74.5 KN despite the fact that it would have failed at the same load as Carbon if it did not fail due to the weak point mentioned earlier.

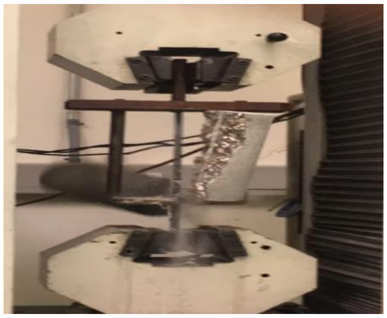

Figure 5: Carbon FRP Reinforced Cylinder

Figure 6: Basalt FRP Reinforced Cylinder

Table 2: Bond Test Results

Specimen	Failure Mode	Failure Load
Steel	Ductile Failure in Steel Bar	70 kN
Carbon FRP	Cylinder split in half (Figure 5)	87 kN
Basalt FRP	Crack along centre line but failure about a crack in top third (Figure 6)	74.5 kN

4.2.2 Beams

The prepared beams were tested using a four-point bending test as described in the experimental program tests section of the report. This particular setup was chosen in order to create a region of zero shear and a constant maximum moment in the beams. As seen in (figure 3) cracks initiated in the constant moment region then stretched towards the supports. In addition to that, a horizontal crack formed at the top of the beam between the 2 loading points.

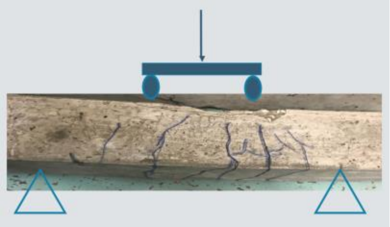

Figure 7: The beam after testing.

4.2.2.1 Steel Reinforced Control Beam

This beam carried an ultimate load of 10.7 t. By using the Whitney stress block this beam was estimated to carry an ultimate load of 8.19 t. This minor discrepancy is due to factors of safety included and theoretical variable implied in the equations. The load vs deformation at mid-span of the beam curve (Figure 7) was obtained in addition to the load vs strain curve obtained from the attached strain gauges was also developed from which the energy absorbed by the beam and the ductility index (Equation 2) was calculated to indicate the ductility of the steel beam to be compared with the remaining specimens.

$$[1]\ \text{Ductility Index} = \frac{\text{Deformation at ultimate Load}}{\text{Deformation at Yield Load}}$$

Table 3: Ductility Parameters of Steel Beam

Energy Absorbed by Beam	93,134 kg.mm	Ductility Index	4.12

4.2.2.2 Carbon FRP Reinforced Beam

This beam carried an ultimate load of 12.9 t, while it was theoretically expected to carry 20.6 t. This extreme discrepancy is due to the FRP bars having a very large deformation and it is incompatible for such a deformation to occur between 2 cracks therefore the stresses in the system are released by slippage in the carbon FRP bars from the concrete. The load vs deformation at mid-span of the beam curve (Figure 7) was obtained in addition to the load vs strain curve (Figure 4) obtained from the attached strain gauges was also developed from which the energy absorbed by the beam and the ductility index was calculated to indicate the ductility of the carbon FRP beam to be compared with the remaining specimens.

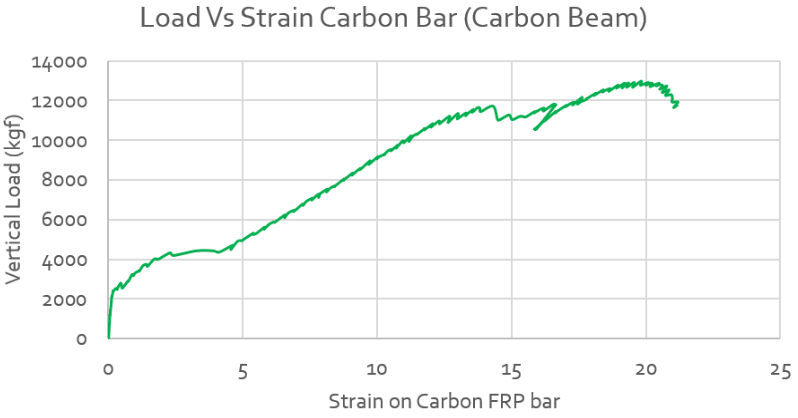

Figure 8: Load Vs Strain Carbon FRP Beam

Table 4: Ductility Parameters of Carbon FRP Beam

Energy Absorbed by Beam	172,493 kg.mm	Ductility Index	5.4

4.2.2.3 Basalt FRP Reinforced Beam

This beam carried an ultimate load of 9.5 t, while it was theoretically expected to carry 14.5 t. This discrepancy is smaller than that of the carbon FRP reinforced beam, due to minimal slippage in the bars due to the sand coating on the basalt FRP bars that improves their bond with the concrete. The load vs deformation at mid-span of the beam curve was obtained (Figure 7) in addition to the load vs strain curve (Figure 5) obtained from the attached strain gauges was also developed from which the energy absorbed by the beam and the ductility index was calculated to indicate the ductility of the basalt FRP beam to be compared with the remaining specimens.

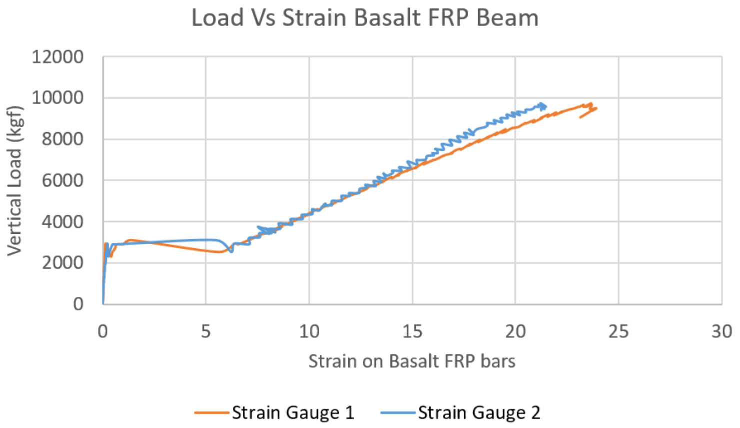

Figure 9: Load Vs Strain Basalt FRP Beam

Table 5: Ductility Parameters of Basalt FRP Beam

Energy Absorbed by Beam	64,780 kg.mm	Ductility Index	3.3

4.2.2.4 Hybrid Beam

The hybrid beam solution was proposed to enhance the ductility of the basalt FRP beam, as it alone had the least ductility index and energy absorbed by the beam which both indicate the low ductility of the basalt FRP beam. The load vs deformation at mid-span of the beam curve (Figure 7) was obtained in addition to the load vs strain curve (Figure 6) obtained from the attached strain gauges was also developed from which the energy absorbed by the beam and the ductility index was calculated to indicate the ductility of the hybrid beam to be compared with the remaining specimens. The beam carried an ultimate load of 11.2 t, while the theoretically calculated was 11.95 t.

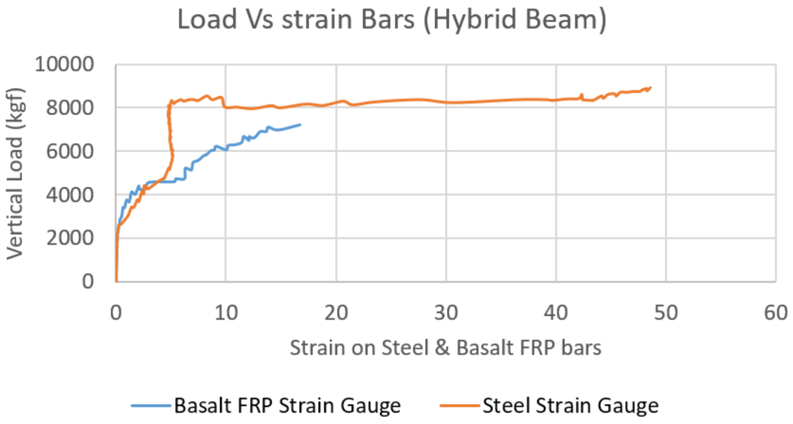

Figure 10: Load Vs Strain Hybrid Beam

Table 6: Ductility Parameters of Hybrid Beam

Energy Absorbed by Beam	201,556 kg.mm	Ductility Index	5.4

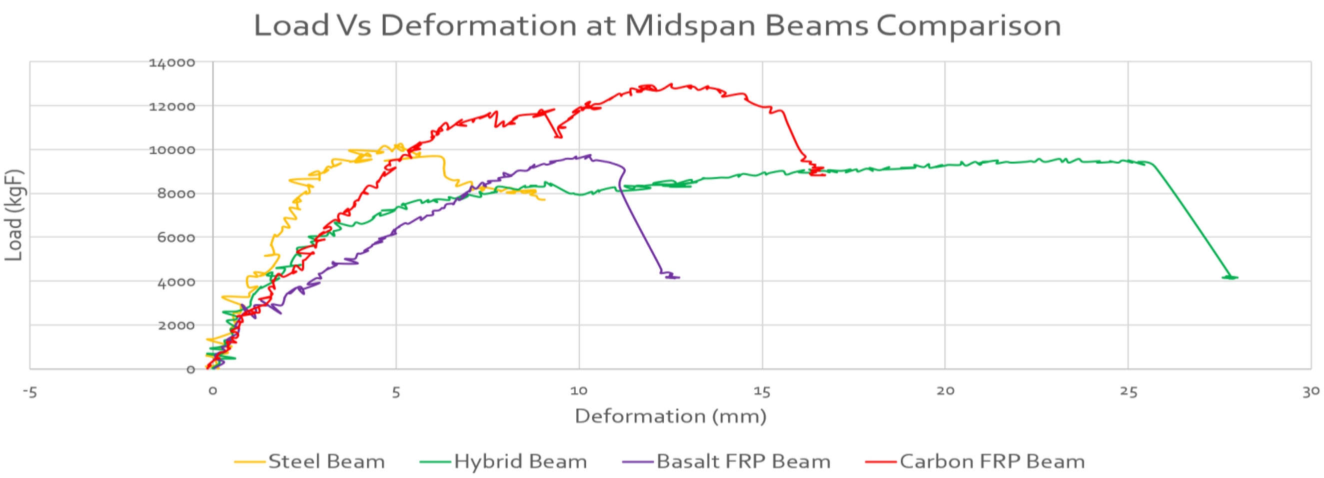

Figure 11: Load Vs Strain Hybrid Beam

Table 7: Comparison of Ductility Parameters

Beam	Steel	Carbon FRP	Basalt FRP	Hybrid
Energy Absorbed by Beam	93,134 kg.mm	172,493 kg.mm	64,780 kg.mm	201,556 kg.mm
Ductility Index	4.12	5.4	3.3	5.4

4.2.3 Column

4.2.3.1 12 mm Diameter Category

The strain was obtained from the load vs strain curve and the energy absorbed by the columns was calculated form the area under the load vs deformation curve. On the other hand, a much higher strain in the carbon FRP bars was created at the same load. After the cracking of the concrete occurred, the CFRP bars kept carrying part of the stress, therefore a higher strain was generated. The energy absorbed by the carbon FRP column was less than that of the steel column and this was shown by the drastic failure which was extremely catastrophic as the column failed by suddenly bursting out.

Table 8: Comparison of Column Results

Column Reinforcement	Ultimate Load (t)	Strain in Bars at Ultimate Load	Energy absorbed by Column (t.mm)
Steel (12 mm)	69	1453	492
Carbon FRP (12 mm)	66	2162	436
Steel (10 mm)	55	2050	264
Basalt FRP (10 mm)	59	1888	731

4.2.3.2 10 mm Diameter Category

The second steel control column was compared to the BFRP column where reinforcement for both was diameter 10 bars. The BFRP column carried an ultimate load 7% higher than the steel column. The energy absorbed by the Basalt FRP column was three times higher than the steel column indicating that modes of failure were visible without suddenly failing.

5.0 Conclusions

- Basalt FRP bars are currently produced in different countries worldwide & can be used in concrete
- Both Basalt & Carbon FRP bars can carry ultimate stresses higher than steel conjugate bars but with significant reduction in ductility
- FRP bars both from basalt & carbon have good resistance to temperature at least up to 100 ˚C
- The hybrid section gave the highest ductility index compared to all other sections tested
- In both applications, the beams & columns, the Basalt FRP bars showed considerably high results that invite their use in reinforced concrete industry.
- There is a significant increase in the initial cost of both FRP bars compared to steel, yet such increase is expected to diminish gradually upon wider use keeping in mind other unique advantages such as corrosion resistance
- FRP bars, both Basalt and Carbon possess superior resistance to acids and alkalis

6.0 Recommendations

- Expand this work on much larger specimens and concrete mixes for longer durations to validate the findings.
- To reduce errors in values of results of the tensile test on the individual bars, attach strain gauges to rather measure their own strain.
- Increase the number of strain gauges used on bars in columns & beams in case a technical error causes the gauges to stop working
- To further understand thermal stability of candidate bars, measure their tensile strength at increments of temperatures to establish a relationship between temperature exposure and loss in mechanical properties
- Test the durability of bars upon exposure to more harsh environments at elevated temperatures
- In the reinforced concrete applications of the candidate bars use high strength concrete to explore different failure modes
- Consider the use of Basalt FRP bar as well as Carbon FRP bars in structures subjected to corrosion and chemical attack
- Apply an epoxy coat on Carbon FRP bars while using them as a reinforcement for concrete.
- Suggest a hybrid system at early implementation of Basalt FRP bars to capitalize on its high ductility properties
- Promote the manufacturing and production of basalt fibers in order to contribute to minimizing its cost
- It is aspired for such new material to be covered in a newer version in the Egyptian code to facilitate its wider use

7.0 References

JR Mackechnie, and MG Alexander. *Repair Principles for Corrosion-damaged Reinforced Concrete Structures.* Publication no. 5. Department of Civil Engineering, University of Cape Town. 2001.

Luna Salh. *Analysis and Behaviour of Structural Concrete Reinforced with Sustainable Materials*. Report. School of Engineering, University of Liverpool. University of Liverpool, 2014.

ASTM D7205, Standard Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars 2016, www.astm.org.

Fareed Elgabbas, Vincent Patrick, Ehab Ahmed, and Brahim Benmokrane. *Experimental Testing of Basalt- fiber-reinforced Polymer Bars in Concrete Beams*. Report. Department of Civil Engineering, University of Sherbrooke.

Richard E. Prince. *Fibre Reinforced Polymers Characteristics and Behaviors*, Prince Lund Engineering.