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Geopolymer concrete beam strengthening with glass fibre reinforced polymer

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Scientific paper - Preliminary note

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Geopolymer concrete beam strengthening with glass fibre reinforced polymer

The experimental evaluation of effectiveness of the externally bonded Glass Fibre Reinforced Polymer (GFRP) in the strengthening of the geopolymer reinforced concrete beams is presented in the paper. Bending tests were conducted until failure to enable full understanding of flexural behaviour of the GFRP strengthened beams, and other characteristics such as the load-deflection behaviour, load-stiffness behaviour, ductility, and failure modes. Test results show that GFRP strengthened beams exhibit a higher load bearing capacity, minimum deflection, enhanced ductility, and better energy absorption characteristics, and that all these properties are dependent on the number of wrapping layers used.

Key words:
geopolymer, GFRP fabrics, strengthening, flexural behaviour, external wrapping

Prethodno priopćenje

Kumutha Rathinam, Basanth Babu Koattaiveedu Mohanram, Vijai Kanagarajan

Utjecaj polimera armiranih staklenim vlaknima na čvrstoću greda od geopolimernoga betona

U radu je opisano eksperimentalno ispitivanje učinkovitosti vanjskog omota od polimera armiranog staklenim vlaknima (eng. *Glass Fibre Reinforced Polymer* - GFRP) na ojačanje greda od betona armiranog geopolimerom. Provedena su ispitivanja savijanjem do sloma kako bi se u potpunostidobio uvid u savojna svojstva greda ojačanih GFRP-om, kao i ostala svojstva, poput odnosa sila-progib,sila-krutost, žilavost i oblici sloma. Rezultati ispitivanja pokazali su da grede ojačane GFRP-om imaju veću nosivost, minimalan progib, povećanu žilavost te bolje apsorbiraju energiju, a sva navedena svojstva ovise o broju slojeva kojima su grede obložene.

Ključne riječi:
geopolimer, GFRP, ojačanje, savojna svojstva, vanjsko omatanje

Vorherige Mitteilung

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Einfluss von glasfaserverstärkten Polymeren auf die Festigkeit von Trägern aus Geopolymerbeton

In dieser Arbeit werden experimentelle Untersuchungen zur Wirksamkeit von Ummantelungen mit faserverstärkten Polymeren bei der Verstärkung von Trägern aus mit Geopolymer armiertem Beton beschrieben. Biegeversuche bis zum Bruch wurden durchgeführt, um die Biegeeigenschaften, das Verhältnis Kraft-Durchbiegung, Kraft-Steifigkeit, sowie Robustheit und Versagensformen bei mit GFRP verstärkten Trägern vollkommen zu erfassen. Die Versuchsergebnisse haben gezeigt, dass die verstärkten Träger eine größere Tragfähigkeit, eine minimale Durchbiegung und eine erhöhte Robustheit vorweisen, sowie mehr Energie absorbieren. Alle aufgeführten Eigenschaften hängen von der Anzahl der Ummantelungsschichten ab.

Schlüsselwörter:
Geopolymer, GFRP, Verstärkung, Biegeeigenschaften, Ummantelung

1. Introduction

Rapid deterioration of infrastructure is becoming a major challenge faced by concrete designers worldwide. The need to have a higher load-carrying capacity in many existing buildings constructed for some specific purpose has led to the renovation or extension of such buildings. In this respect, the existing structures need to be re-assessed and may require strengthening to meet more stringent load requirements. Rehabilitation of deteriorated concrete structures is a heavy burden from the socio-economic point of view since it leads to significant user costs [1]. Changing social needs, more stringent design standards, higher safety requirements, deterioration of existing reinforced concrete infrastructure, all this contributes to the constant rise in structural strengthening demands [2]. Other reasons for deterioration of RC members include reinforcement corrosion, spalling of concrete etc., which is caused by age and exposure to adverse environments. Although many different repair and strengthening materials and techniques are being proposed, it is very important that the composite repair system be tailored to serve the intended use, while also being able to meet more stringent serviceability requirements. Conventional concrete structure strengthening techniques include jacketing, shotcreting, plate bonding, etc. These techniques are time consuming, labour intensive, and require skilled manpower. Composite materials have been in existence for quite a long time, but their use in civil engineering infrastructure applications, based on an advanced technology, is still at a developing stage. The World's construction industry is looking forward in appreciating the unique terminology, as offered by these composites in incorporation of reinforcement in form of polymer matrix. The use of externally bonded fibre-reinforced polymer (FRP) sheets and strips has recently been established as an effective tool for rehabilitating and strengthening reinforced concrete structures. A lot of experimental investigations have been reported on the behaviour of concrete beams, strengthened for flexure using externally bonded FRP plates, sheets, or fabrics.

On the other hand, the process of cement production is highly energy-intensive, while also causing emission of greenhouse gases like CO_2. The global cement industry contributes with approximately 2.8 billion tons of the greenhouse gas emissions annually [3, 4]. Since the conventional reinforced concrete is less durable in some environmental conditions, the geopolymer technology, introduced by Davidovits [17], provides a binder that is a plausible alternative to the Ordinary Portland Cement (OPC). The alkali activation of fly ash through polymerization in the presence of sodium hydroxide and sodium silicate solution, results in the geopolymer concrete. The performance of geopolymer materials when exposed to acid solutions has proven to be superior to that of the ordinary Portland cement [5]. Similar to the conventional reinforced concrete, the geopolymer concrete is suitable for structural applications, and the design provisions given in current standards and codes can be used to design reinforced fly ash-based geopolymer concrete structural members [6]. Obviously, the strengthening techniques used for conventional concrete can also be used for geopolymer concrete structures. This paper presents results of an experimental investigation on geopolymer reinforced concrete beams strengthened with GFRP.

2. Experimental programme

2.1. Materials used

2.1.1. Fly ash

The low calcium fly ash (ASTM class F) collected from the Mettur Thermal Power Station, Tamil Nadu, India, was used as the source material for the preparation of geopolymer concrete. The specific gravity of fly ash is 2.46. The chemical composition of fly ash is given in Table 1.

Table 1. Chemical characteristics of fly ash

	Characteristics	Test results [mas %]
1.	Loss on ignition	0.72
2.	Silicon dioxide (SiO_2)	60.24
3.	Aluminium oxide (Al_2O_3) + iron oxide (Fe_2O_3)	35.34
4.	Iron oxide (Fe_2O_3)	7.84
5.	Aluminium oxide (Al_2O_3)	27.50
6.	Calcium oxide (CaO)	0.59
7.	Magnesium oxide (MgO)	0.85
8.	Total sulphur as sulphur trioxide (SO_3)	0.03
9.	Sodium oxide (Na_2O)	0.00
10.	Potassium oxide (K_2O)	0.02
11.	Sulphide sulphur (S)	0.00
12.	Insoluble residue	90.61

2.1.2. Aggregates

Fine and coarse aggregates used in concrete industry were used in this study. The fine aggregate was sieved using the 4.75 mm sieve to remove all foreign matter. The specific gravity and fineness modulus of the fine grained aggregate was found to be 2.66 and 2.69, respectively. Coarse aggregates with the maximum size of 12 mm, having a specific gravity of 2.96 and fineness modulus of 5.30, were used.

2.1.3. Alkaline solution

The sodium hydroxide solution mixed with the sodium silicate solution was used as an alkaline activator for geopolymerization. The commercially available sodium hydroxide in the form of flakes was used in this study. The sodium silicate is available commercially in liquid form and hence it was used in such form.

2.1.4 Ground granulated blast furnace slag (GGBS)

The GGBS is a waste product, generated from iron industries. The GGBS used in this study was obtained from M/s Quality Polytech, Mangalore, India. Its specific gravity is 3.11. The Chemical composition of GGBS is given in Table 2.

Table 2. Chemical characteristics of GGBS

	Characteristics	Test results [mas %]
1.	Loss on ignition	0.62
2.	Insoluble residue	0.32
3.	Magnesia content	8.15
4.	Sulphide sulphur	0.59
5.	Sulphite Content	0.41
6.	CaO	34.86
7.	SiO_2	32.78
8.	Al_2O_3	22.40
9.	Fe_2O_3	1.10
10.	Mangan	0.08
11.	Chemical moduli $CaO+MgO+SiO_2$ $CaO+MgO/SiO_2$ CaO/SiO_2	 75.79 1.31 1.06

2.1.5. Water and superplasticizer

Distilled water is used throughout this study. Superplasticizer with the brand name of Conplast SP 430, which is a chloride free superplasticizing admixture based on sulphonated naphthalene polymers, manufactured by Fosroc Chemicals Pvt. Ltd., India, was used in this study to improve workability of concrete. It is supplied as a brown solution that instantly disperses in water.

2.1.6. GFRP Fibre

The unidirectional E-Glass fibre of type Woven-Rovings, compliant with IS:11273 [14], available under the commercial name of Binani, and fabricated by Goa Glass Fibre Limited, India, was used in this experimental program. The fibre mat is 0.6 mm in thickness, and its density amounts to 610 gm/m². The E-Glass fibre can be modelled into any kind of shape. A general purpose polyester resin is used as an adhesive to ensure sufficient bonding between the GFRP sheets and the geopolymer concrete beams. It is a three-part system consisting of the resin, accelerator and catalyst. As per manufacturer's specifications, the accelerator and catalyst are used in the quantity of 1.5 % of the total weight of resin.

2.2. Mix proportioning of geopolymer concrete

In the OPC concrete mix design, the proportion of coarse and fine aggregates will range from 75 % to 80 % by mass. As an average, this proportion is taken to be 77 % in the design of geopolymer concrete. The proportion of fine grained aggregate in the total aggregate content is 30 % [7]. It was established based on literature that an average density of the fly ash-based geopolymer concrete is similar to that of the OPC concrete (2400 kg/m³). The combined mass of the alkaline liquid and fly ash can be defined once the density of concrete is established. The ratio of the alkaline liquid to fly ash is assumed to be 0.4. Based on this assumption, the mass of alkaline liquid was established. Similarly, the ratio of sodium silicate solution to sodium hydroxide solution is fixed to 2.5, and it served as basis for establishing the mass of sodium hydroxide and sodium silicate solutions. To achieve workable concrete, extra distilled water (other than the water for preparation of alkaline solutions) and the superplasticizer Conplast SP 430 were added to the mix in the quantity of 10 % and 3 % by the weight of fly ash, respectively. Distilled water was used to avoid the effect of unknown contaminants in mixing water [8]. To avoid delayed setting and heat curing [9], 10 % of GGBS was added to fly ash and the mix was designated as F90G10. The mix proportions of geopolymer concrete are given in Table 3.

2.3. Mixing and casting of geopolymer concrete

The weighed quantity (480 g) of Sodium Hydroxide (NaOH) in the form of flakes to suit 12 Molarity (12M) is allowed to dissolve in distilled water and made up to one litre. By trial and error, 300 gms of NaOH solution can be obtained when 120 gms of NaOH flakes are mixed in a makeup jar of 250 ml. Based on this, the sodium hydroxide solution of required quantity is prepared and mixed with the sodium silicate solution one day before the concrete is cast [10]. This waiting time allows solids to fully dissolve in the solution, while also enabling inspection and detection of a badly-mixed solution prior to use. Mixing of dry materials was carried out first in a drum type mixer with 0.062 m³ in capacity. Alkaline solution and the required extra water and superplasticizer were then mixed. The freshly mixed geopolymer concrete was placed in three layers into the beam mould. Before casting, machine oil was tarnished on the inner surfaces of the cast iron mould. Each layer was then vibrated for 15 seconds using a mechanical vibrator. After thorough compaction, the top surface was levelled using a smooth trowel. The moulds were left at room temperature for ambient curing.

Table 3. Mix proportions of geopolymer concrete

Mix ID	Fly ash [kg/m³]	GGBS [kg/m³]	NaOH [kg/m³]	Na_2SiO_3 [kg/m³]	Fine aggregate [kg/m³]	Coarse aggregate [kg/m³]	Water [kg/m³]	Superplasticizer [kg/m³]
F90G10	394.30	39.43	45.10	112.60	554.40	1293.40	39.43	11.83

2.4. Specimen details

A total of 7 beams were cast and tested until failure. The beams were divided into two groups, viz. Group A and Group B, based on the type of the GFRP wrapping scheme. The Group A consisted of 3 beams which were U-wrapped with the GFRP mat with one layer, two layers, and three layers each. The Group B consisted of another 3 beams bonded with the external GFRP mat with one layer, two layers, and three layers at their soffits. One beam was a control specimen without external GFRP laminates. In addition to this, 3 cubes measuring 150 mm x 150 mm x 150 mm, 3 cylinders of 150 mm in diameter and 300 mm in height, and 3 prisms measuring 500 mm x 100 mm x 100 mm, were also cast and tested in order to find the compressive strength, split tensile strength, and flexural strength of geopolymer concrete, respectively. The split tensile strength of concrete was determined using cylinder specimens as per IS: 5816-1999 [16]. For ease of identification, the beams externally U-wrapped with E-Glass fibre mat were designated as U1, U2, U3, and the beams with GFRP plates at the soffit were named as S1, S2 and S3 for one, two, and three layers, respectively. The beam without the GFRP wrap was designated as a control beam, which is common for both groups. Each glass fibre layer was 0.6 mm in thickness. The beam geometry is shown in Figure.1. The beams were reinforced with two numbers of 10 mm diameter High Yield Strength Deformed (HYSD) bars at the bottom, and two numbers of 8mm diameter HYSD bars at the top, with the 8 mm diameter stirrups at 100 mm centre to centre. All beams were tested under the two-point loading, with a support to support distance of 1.5 m. The loads were applied 500 mm away from each support of the beam.

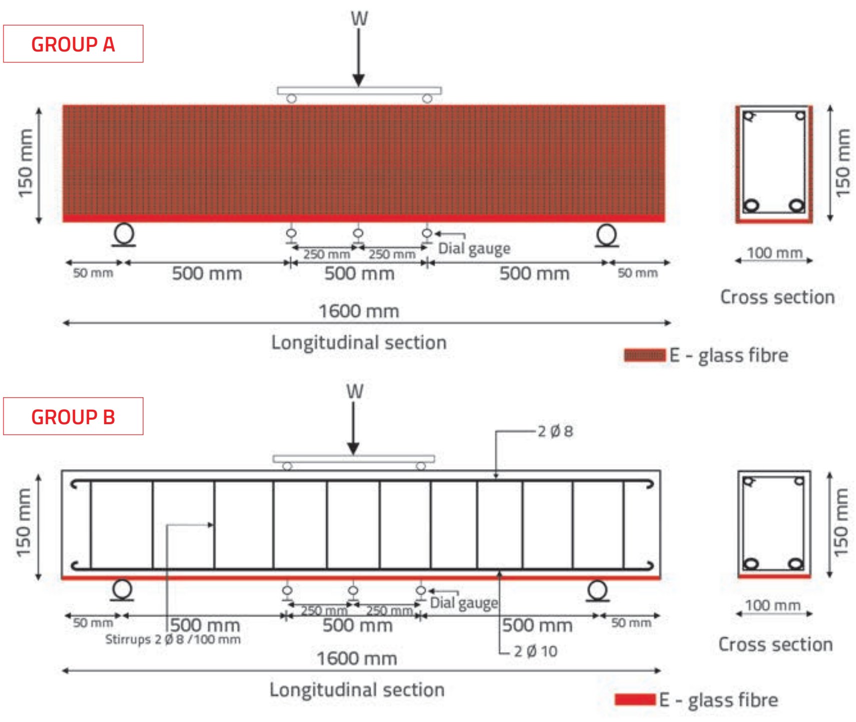

Figure 1. Specimen details: a) Group A beams - front view and cross section; b) Group B beams - longitudinal profile and cross section

2.5. Wrapping of geopolymer beams

The concrete surface was initially roughened by pointing, which was followed by vacuum cleaning to remove any dust or loose particles from the concrete surface. The three-component polyester resin bonding adhesive was prepared in accordance with the manufacturer's recommendations and applied to the concrete surface by paint brush. The mixing was conducted in a plastic container to prevent resin sticking [11]. The first layer of the E-Glass fibre sheet was then placed by hand and pressed onto the adhesive to squeeze out excess resin, and to eliminate air bubbles. Additional GFRP layers were applied in the same way onto the uncured wet adhesive. The complete application was subsequently left to cure for at least 7 days at room temperature. The bottom-face GFRP sheets were applied with the beams turned upside down. The entire process was carried out with caution (mandatory use of hand gloves), since the E-Glass fibres may cause itching.

Figure 2. Test setup

2.6. Test arrangement

The beams were tested in the force-controlled Universal Testing Machine, 1000 kN in capacity. All beams were tested up to ultimate load, under two-point loading over a simply supported span of 1500 mm. Both ends of the beam were free to rotate and translate under the load. To measure the deflections, three dial gauges were placed one at the centre and the other two under the loading points of the beam. The load was applied in 1 kN increments until the yield of the tensile reinforcement. A small load of 2 kN was slowly applied at the beginning, so as to ensure the proper seating of beams on rollers and proper functioning of the instruments. The trial load was applied again slowly and the beam was tested to failure by applying the load in increments, and the observations such as mid-span deflections at each load step, first crack load, and ultimate load, were recorded carefully. The test setup is shown in Figure 2.

3. Results and discussion

3.1. Mechanical properties

The average compressive strength, split tensile strength, and flexural strength of geopolymer concrete at 28 days amounted to 22.66 N/mm^2, 2.76 N/mm^2, and 5.56 N/mm^2, respectively.

3.2 First crack and ultimate load

The summary of test results for all beams, showing the first crack load, deflection at first crack load, and deflection at the point of failure, is given in Table 4. . The first crack load in the control beam is 6.80 kN, while for beams U1,U2,U3,S1,S2 and S3 , the first crack load forms at 8.25 kN, 8.90 kN, 9.78 kN, 7.40 kN, 8.10 kN, and 8.80 kN, respectively. It can be observed that all beams exhibited some delay in the formation of first crack, when compared to that of the control beam. The improvement in ultimate loads of beams U1, U2 and U3 was 10.57 %, 14.83 % and 18.60 %, respectively, as compared to the control beam. Similarly, in case of group B beams, the increase in ultimate loads was found to be 7 %, 11.40 %, and 15 %, for one, two, and three layers, respectively, when compared to the unwrapped beam. It can be seen that in both groups of beams, the beam with 3 GFRP layers exhibits the maximum load carrying capacity when compared to other beams. This shows that the ultimate load carrying capacity increases with the number of GFRP layers. The comparison between the ultimate load of all beams and that of the control beam is shown in Figure 3.

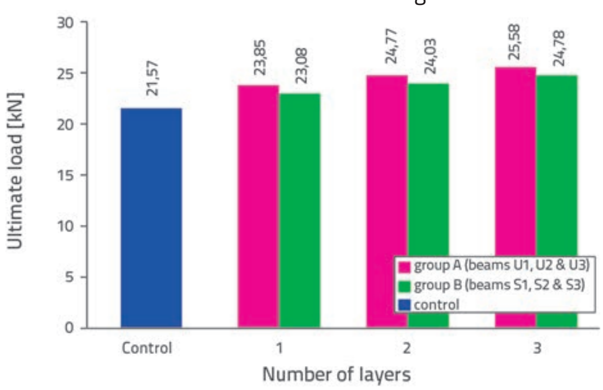

Figure 3. Effect of number of layers on ultimate load

3.3. Load-deflection response

In Figure 4, the load-deflection response of the Group A beams is compared with that of the control beam. Figure 5 represents the load-deflection response of the Group B beams, along with the response of the control beam.

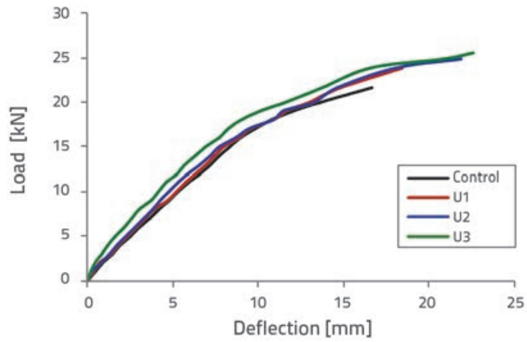

Figure 4. Load - deflection response, Group A beams

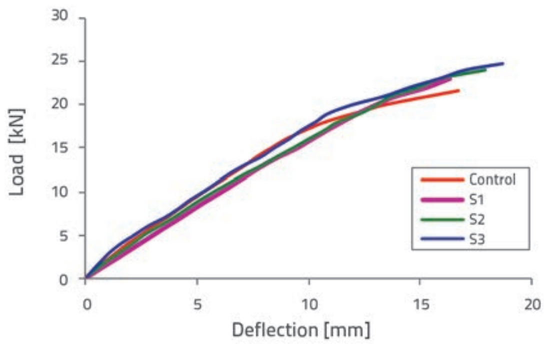

Figure 5. Load - deflection response, Group B beams

The beam U3 exhibited the largest deflection. It had a maximum deflection of 22.53 mm, which is by 35.15 % more than that of the Control beam (16.67 mm). On the other hand, the beam S1 exhibited the lowest deflection of 16.30 mm, which is by 2.22 % lower than that of the control beam. With the exception of the beam S1, all strengthened beams exhibited greater deflections than those of the control beam at their ultimate loads, which shows that the ductility of the beams increased due to the presence of GFRP layers. For comparison, deflections of wrapped beams were compared at a load value corresponding

Table 4. Summary of test results

Beam ID	First crack load [kN]	Deflection at first crack load [mm]	Ultimate load [kN]	Deflection at ultimate load [mm]	Stiffness at ultimate load of control beam [kN/mm]
Control	6.80	3.52	21.57	16.67	1.29
U1	8.25	4.07	23.85	18.40	1.46
U2	8.90	4.23	24.77	21.80	1.48
U3	9.78	4.10	25.58	22.53	1.58
S1	7.40	4.49	23.08	16.30	1.48
S2	8.10	4.60	24.03	17.92	1.50
S3	8.80	4.62	24.78	18.68	1.54

to the ultimate load of control beam, and it was established that the deflection of beams U1, U2, and U3 decreased by 11.33 %,12.6 %, and 18 %, respectively. Similarly, in case of the Group B beams, the deflection of beams S1, S2, and S3 decreased by 12.3 %, 12.9 %, and 13.9 %, respectively, at ultimate load of the control beam. The deflection values of each and every beam were compared at ultimate load of other beams, as shown in figures 6 and 7, respectively. In all cases of beam strengthening, it was established that with an increase in the number of layers of wrapping, their deflection decreases considerably with reference to the deflection at ultimate load of the control beam.

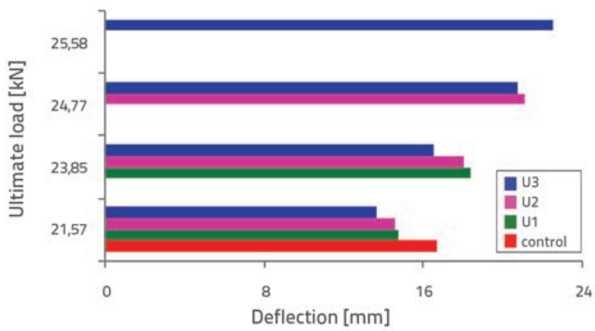

Figure 6. Comparison of deflection at ultimate load, Group A beams

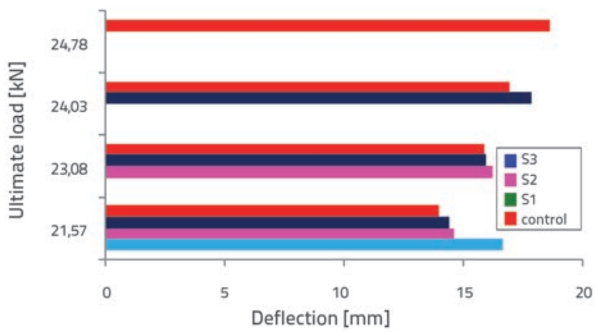

Figure 7. Comparison of deflection at ultimate load, Group B beams

3.4. Load-stiffness characteristics

The load-stiffness curves of both groups of beams are presented in figures 8 and 9.

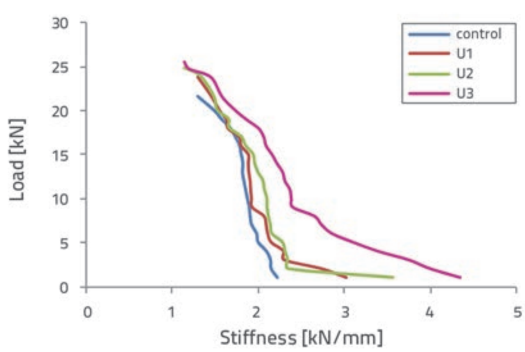

Figure 8. Load versus stiffness, Group A beams

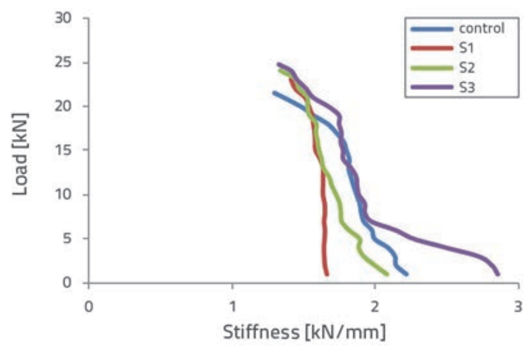

Figure 9. Load versus Stiffness, Group B beams

The beam U3 exhibited the highest stiffness of all strengthened beams at ultimate load of the control beam. This beam exhibited an increase in stiffness of 22.50 % when compared to that of the control beam. Similarly, beams U1 and U2 exhibited an increase in stiffness of 13.17 % and 14.73 %, respectively, when compared to the stiffness of the control beam. In case of Group B beams, the increase in stiffness amounted to 14.72 %, 15.50 %, and 16.27 %, respectively, when compared to the control beam stiffness. It can be observed that all strengthened beams, both in Group A and Group B, exhibited a higher stiffness when compared to that of the control beam. The comparison of stiffness of all beams at ultimate load of the control beam is shown in figures 10 and 11.

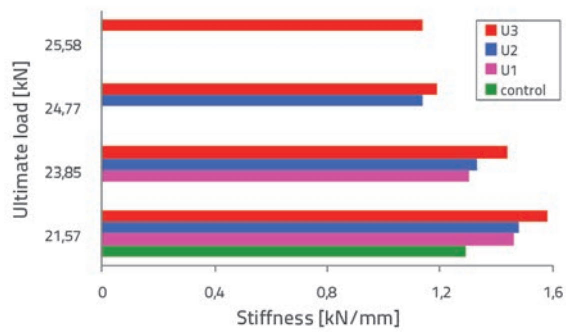

Figure 10. Comparision of stiffness, Group A beams

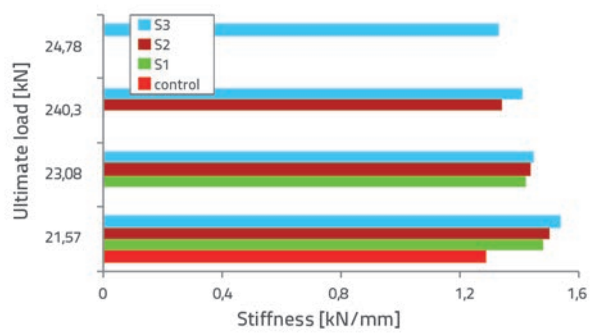

Figure 11. Comparison of stiffness, Group B beams

3.5. Energy absorption characteristics

For all beams tested, the energy absorption is obtained by calculating the area under the load deflection curve, and the corresponding values are given in Joules (J). The comparison of energy absorption capacity is shown for all beams in Figure 12. The energy absorption of the control beam amounts to 231.3 J. The energy absorption of the U1, U2 and U3 increases by 40.54 %, 67.56 %, and 100 %, respectively, when compared to that of control beam. Similarly, the energy absorption of S1, S2, and S3 increases by 8.43 %, 20.72 %, and 38.55 % when compared to the unwrapped beam. Among all beams, the beam U3 attained the highest energy absorption when compared to the control beam. When comparing the Group A and Group B beams, the beams that were wrapped with GFRP layers on three sides present better energy absorption characteristics.

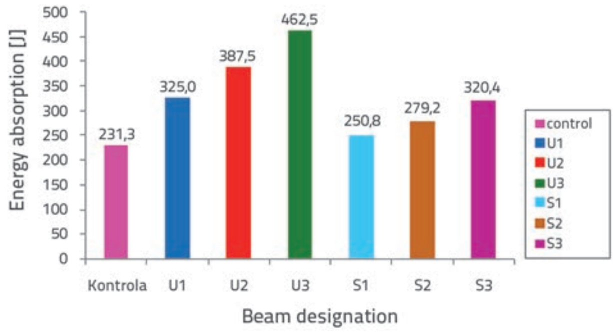

Figure 12. Comparison of energy absorption of beams

3.6. Ductility

The ductility of a beam can be defined as its ability to sustain inelastic deformation without loss in load carrying capacity prior to failure. It is usually calculated for conventional reinforced concrete structures as the ratio of curvature, deflection, or rotation at ultimate load to yielding of steel [12]. Ductility Index is the ratio of the deflection at ultimate load to the deflection at yield. The comparison of ductility indexes is shown in Figure 13.

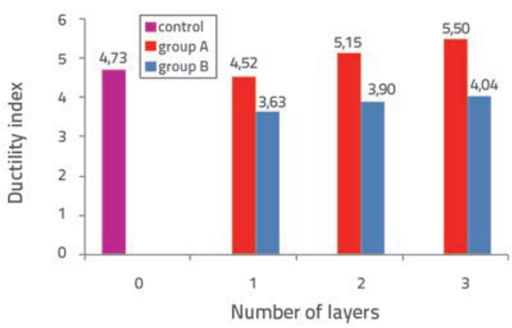

Figure 13. Comparison of ductility Indexes

The control beam had a ductility index of 4.73. Group A beams had ductility indexes of 4.52, 5.15, and 5.50, for one, two and three GFRP layers, respectively. While the beams U2 and U3 attained a greater ductility than the control beam, the beam U1 attained a lower ductility index (4.52) than the control beam, which reveals that a single GFRP layer is not sufficient to provide sufficient ductility to the member. Similarly all beams in Group B attained a lower ductility index of 3.63, 3.90, and 4.04, respectively, even though they exhibited higher ultimate load carrying capacity as compared to the control beam. However, the ductility index increased with an increase in the number of layers. This may be due to earlier yielding of steel over the mid-span [13]. All beams strengthened with U wraps were assumed to have sufficient ductility.

3.7. Failure modes

All beams were tested until failure so that the data can be acquired about the influence of E-glass fibres on the flexural behaviour of geopolymer reinforced concrete beams. The control beam failed in flexure, while the behaviour of failure is ductile. For the entire Group A beams, failure occurred in-between the load points at the compressive zone. The failures were associated with debonding of the glass fibre wraps from the sides of the beam, accompanied with a sudden, loud noise. The beam carried practically no load after failure. Flexural cracks due to rupture of fibre sheets were noted in Group A beams, whereas in Group B beams the flexural cracks started to spread from the bottom of the beams. Rupture of fibre sheets may be due to hidden cracks (due to U-wrapping) that would have occurred earlier. For Group B beams, the cracking pattern was almost the same as that of the control beam. It was characterized by extension of a flexural-shear crack towards the points of loading with shear cracks connected to it. The failure of beam with one layer at the soffit (S1) occurred at the concrete-adhesive interface since the debonded laminate was observed to be smooth with concrete debris bonded to it. Beams S2 and S3 exhibited tensile rupture of GFRP sheets near the left-hand load point and in-between the load point, respectively. Rupture of GFRP sheets was sudden and accompanied by noise. This points to rapid release of energy and total loss of load carrying capacity, followed by the concrete crushing at the top of the beams. At other locations, the sheet remained intact in beams with the bonded anchorage. In both cases of failure, i.e. for Group A and Group B beams, it was observed that the laminates are attached with small sized peeled-out concrete blocks. Figure 14 shows the failure mode of Group A beams, and the failure mode of Group B beams is shown in Figure 15.

Figure 14. Failure of Group A beams

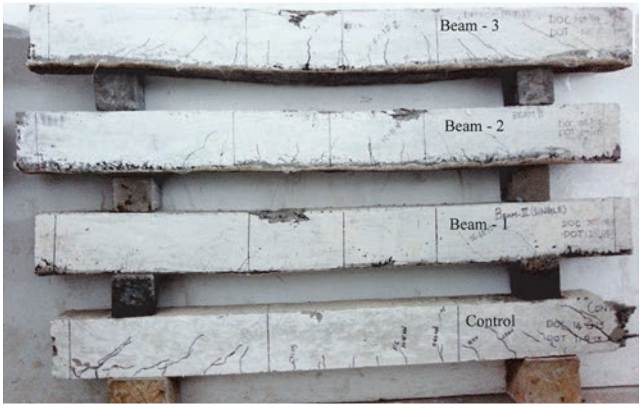

Figure 15. Failure of Group B beams

4. Conclusions

Based on the experimental investigation described in this study, the following conclusions are drawn:

- In case of beams wrapped on three sides, the ultimate load, stiffness, ductility and energy absorption increase with an increase in the number of GFRP layers, compared to the beam without any GFRP wrap. However, in the case of beams provided with GFRP sheets at their soffits, and even though the ultimate load, stiffness and energy absorption values increase with respect to the control beam, the beams do not exhibit great ductility, as shown by lower ductility factors.
- At the same value of applied load, all strengthened beams exhibited smaller mid-span deflections, compared to the corresponding control beam.
- Sudden debonding of GFRP sheets was the dominant failure mode of the strengthened beams tested. This mode of failure was not prevented even if more than one layer was used. Cracks that occurred are smaller and more evenly distributed in both beam groups tested.
- Even though considerable research has been made to study the effect of GFRP wraps on the behaviour of reinforced concrete (R.C.) structural members, no work has so far been found in literature that would explore structural behaviour of geopolymer reinforced concrete members, strengthened with GFRP using various wrapping configurations. Hence an initiative has been made through the present investigation to see how far the composite materials can effectively be used for the purpose of strengthening of members made of concrete without any cement. However, further studies are required so as to enable a more effective use of composite wrapping schemes in geopolymer concrete.

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REFERENCES

[1] Bruhwiler, E.: Rehabilitation and strengthening of concrete structures using Ultra High Performance fibre reinforced concrete, *Concrete Repair, Rehabilitation and Retrofitting – III*, Taylor and Francis, 2012.

[2] Godat A., Neale K.W., Labossière P.: Numerical modeling of FRP shear-strengthened reinforced concrete beams, *Journal of Composites for Construction (ASCE)*, 11 (2007) 6, pp. 640-649.

[3] McCaffrey, R.: Climate Change and the Cement Industry, *Global Cem Lime Magazine* (Environmental Special Issue) (2002), pp. 15-19.

[4] Vora, P.R., Dave, U.V.: Parametric studies on Compressive strength of geopolymer concrete, *Procedia Engineering* 51 (2013), pp. 210-219, http://dx.doi.org/10.1016/j.proeng.2013.01.030

[5] Bakharev, T.: Resistance of geopolymer materials to acid attack, *Journal of Cement and Concrete Research*, 35 (2005) 4, pp. 658-670.

[6] Rangan B.V., Sumajouw, D., Wallah, S., Hardjito, D.: Studies on reinforced low–calcium fly ash-based geopolymer concrete beams and columns, *31st Conference on our world in concrete & structures*, pp. 16-17, August 2006, Singapore.

[7] Vijai, K., Kumutha, R., Vishnuram, B.G.: Experimental Investigations on Mechanical Properties of Geopolymer Concrete Composites, *Asian Journal of Civil Engineering (Building and Housing)*, 13 (2012) 1, pp. 89-96.

[8] Vasconcelos, E., Fernandes, S., Barroso de Aguiar, J.L., Pacheco-Torgal, F.: Concrete retrofitting using metakaolin geopolymer mortars and CFRP, *Journal of Construction and Building Materials*, 25 (2011) 8, pp. 3213-3221.

[9] Vijai, K, Kumutha, R., Vishnuram, B.G.: Effect of inclusion of steel fibers on the properties of geopolymer concrete composites, *Asian Journal of Civil Engineering (Building and Housing)*, 13 (2012) 3, pp. 377-385.

[10] Alomayri, T., Shaikh, F.U.A., Low. I.M.: Characterization of cotton fibre reinforced geopolymer composites, *Journal of Composites: Part B: Engineering*, 50 (2013), pp.1-6, http://dx.doi.org/10.1016/j.compositesb.2013.01.013

[11] Puranik, P.R., Vasavada, D.A., Patel, V.R.: Use of Woven Fabrics for strengthening of Reinforced Concrete Beams, *Journal of Engineering Research and Applications*, 4 (2014) 3, pp. 52-58.

[12] Grace, N.F., Sayed, G.A., Soliman, A.K., Saleh, K.R.: Strengthening Reinforced Concrete Beams using Fiber Reinforced Polymer (FRP) laminates, *ACI Structural Journal*, pp. 865-874, 1999.

[13] El-Refaie, S.A., Ashour, A.F., Garrity, S.W.: Sagging and Hogging strengthening of continuous reinforced concrete beams using carbon fibre-reinforced polymer sheets, *ACI Structural Journal*, pp. 446-453, August 2003.

[14] IS: 11273-1992 (Reaffirmed – 2003) : Woven Roving Fabrics of 'E' glass fibre – Specification, *Bureau of Indian Standards*, New Delhi, February 1992.

[15] IS: 516-1959 (Reaffirmed – 2004) : Methods of Test for Splitting Tensile Strength of Concrete Cylinders, *Bureau of Indian Standards*, New Delhi, December 1959.

[16] IS: 5816-1999 (Reaffirmed - 2004): Splitting Tensile Strength of Concrete - Method of Test, *Bureau of Indian Standards*, New Delhi, July 1999.

[17] Davidovits, J.: Geopolymer Cement - a review, Geopolymer Institute, Saint-Quentin, France, January 2013.