EXPERIMENTAL STUDY ON SECTION CURVATURE AND DUCTILITY OF REINFORCED GEOPOLYMER CONCRETE BEAMS

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Abstract: *Geopolymer is a product that can replace cement adhesives in concrete, reduce carbon emissions during construction process and utilize industrial waste to reduce environmental impacts. The ductility of the geopolymer concrete in the reinforced concrete geopolymer structure is an important factor to increase safety of the structure. This article presents the experimental results of the section deformation and ductility of RGPC beams. Structural behaviour of RGPC section and influences on section ductility of RGPC beams are compared with that of traditional reinforced concrete beams, in which the ratio of reinforcing steel has a significant influence.*

Keywords: *steel ratio, ductility, geopolymer concrete (GC), reinforced geopolymer concrete (RGPC) beams*

I. INTRODUCTION

Ductility is an important factor for the safety of structure. Thanks to ductility internal forces in highly loaded parts can be transferred to less loaded parts with strength reserve. This redistribution depends on the deformation capacity of the highly loaded parts and the development of plastic deformation without failure.

Geopolymer is the product of chemical reaction between strong alkaline solution and aluminum and silica rich materials, which can replace cement binder in concrete. The materials used to produce geopolymer concrete are mainly taken from industrial waste such as fly ash, rice husk ash, blast furnace slag ...

Fly ash geopolymer has the potential to replace Portland cement to become an environmentally friendly adhesive used in construction. The results of previous studies show that fly ash geopolymer concrete has flexural tensile strength about 10-30% higher, but the elastic modulus are rated lower than cement concrete of the same compressive strength [3, 6]. In addition to the advantages of low creep and shrinkage, GPC also has higher thermal durability, resistance in acid and aggressive environments than OPC [10, 11]. Therefore, the application of GPC in structural components will result in a significant reduction in the life cycle cost of the product.

Some construction works have been fully built using fly ash geopolymer concrete such as the building of Global Change Institute, the University of Queensland, Wellcamp airport using more than 30 000m^3 [14] ...

However, some aspects of structural behavior of fly-ash geopolymer concrete which are different from that of conventional cement concrete need to be investigated. The ductility of the geopolymer concrete in the reinforced concrete geopolymer structure is an important factor to increase safety of the structure.

II. COMPRESSION BEHAVIOUR OF GEOPOLYMER CONCRETE AND DUCTILITY OF REINFORCED CONCRETE SECTION

2.1. Compression behavior of geopolymer concrete

Compression behavior is an important characteristic of geopolymer concrete. This characteristic show the strength of geopolymer concrete as well as the flexural behavior of reinforced geopolymer concrete beams. The compressive stress-strain relation of fly ash geopolymer concrete is determined according to the Sargin model with the equation below [7]:

$$\sigma = k_3 f_c^{'} \frac{Ax + (D-1)x^2}{1 + (A-2)x + Dx^2} \quad (1)$$

in which: σ - concrete stress; $f_c^{'}$ - cylinder compression strength of concrete; k_3 - maximum compression stress ratio, commonly used $k_3 = 1$.

$$A = \frac{E_c \varepsilon_c}{k_3 f_c^{'}} \quad (2)$$

$$x = \frac{\varepsilon}{\varepsilon_c} \quad (3)$$

ε - compression strain of concrete; ε_c - concrete strain at maximum compression stress.

D - parameter for the slope of descending branch. For geopolymer concrete used in this study, this parameter is adjusted accordingly [7]: $D = 0,65 - 7,25 f_c^{'}.10^{-3}$ (4)

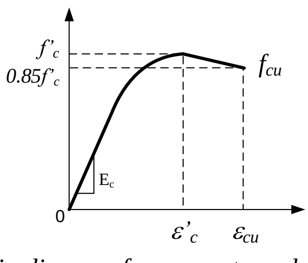

***Figure 1**. Stress - strain diagram for concrete under uniaxial compression*

The ultimate strain ε_{cu} characterizes the deformability of concrete without failure after the maximum stress is reached. This strain varies upon the concrete grade and also on the loop effect of stirrups in the compression zone. According to Eivind Hognestad [4] this value in the compressive stress – strain diagram is taken corresponding to the stress value equal to 85% of maximum stress $f_c^{'}$ on the descending branch. Many authors determine this strain corresponding to the stress ratio of 75% or 80% but the value that is more commonly used conservative for the structural analysis is $f_{cu} = 0{,}85f_c^{'}$ [8] (figure 1).

On that basis, the ultimate strain for geopolymer concrete in the compression zone without loop effect of stirrups can be used as follows [7]:

Table 1. *Maximum compressive strain proposed for analysis [7]*

GPC grade (MPa)	30	40	50
ε_{cu} (‰)	4,00	3,60	3,20

2.2. Ductility of reinforced concrete section

Ductility is understood as the ability of a material, section or structure to develop large plastic deformation without losing strength.

The method for determining ductility of a section or structure is to use its deformation, displacement or rotation. For beam components, ductility index u of a cross section is usually defined as ratio of the ultimate curvature of the section φ_u and the curvature of the section when the reinforcement yields φ_y [1]:

$$u = \varphi_u / \varphi_y \quad (6)$$

The typical moment – curvature relation for a cross section under bending is shown in figure 2 [5]:

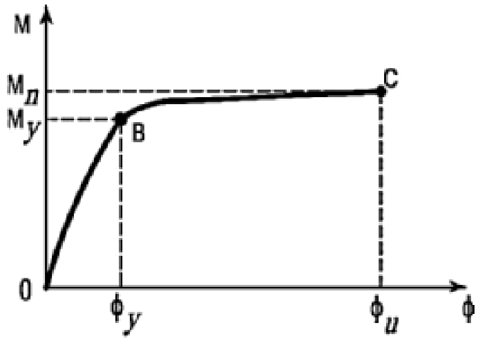

***Figure 2**. Moment - Curvature relation for a cross section under bending [5]*

Section curvature φ is defined as the rotation angle change per unit length [1] as shown in figure 3.

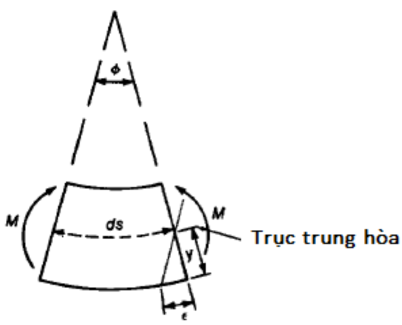

***Figure 3.** Definition of section curvature*

$$\varphi = \frac{\varepsilon}{y} \quad (5)$$

ε - strain at distance y from the neutral axis of the cross section.

The steel ratio will affect the curvature of the section in both plastic state and at failure. For a given cross section of a reinforced concrete beam under bending the ductility of the section will depend on the tensile reinforcement ratio in the beams.

III. EXPERIMENTAL STUDY ON THE SECTION CURVATURE AND DUCTILITY OF RGPC BEAMS

3.1. Materials used

Composition of fly ash geopolymer concrete used for the experiments is shown in table 2 [2]:

Table 2. *Composition of fly ash geopolymer concrete (Kg) [2]*

GPC composition		G_40
Fly ash		375,84
Coarse aggregates	2,36-4,75 mm	64,68
	4,75-9,50 mm	420,42
	9,50-19,0 mm	743,82
	19,0-25,0 mm	65,68
Fine aggregates		554,0
NaOH solution		50,33 (14 M)
Na_2SiO_3 solution		125,83

The mechanical properties of fly ash geopolymer concrete were determined through experiments, as shown in Table 3.

Table 3. *Mechanical properties of fly ash geopolymer concrete (Kg) [6]*

Mechanical properties	Value (MPa)
Characteristic strength, $f_c^{'}$	40,46
Characteristic E-moduls, $E_c^{'}$	26387
Characteristic flexural tensile strength $f_r^{'}$	5,02

3.2. Fabrication of beam specimens

Beams are fabricated from Geopolymer concrete mix G_40 with the above designed composition. Three beam groups are fabricated, each group of 3 beams with different reinforcement ratios. The dimensions and reinforcement layout in the beams are shown in figure 4. The parameters of the beam materials are shown in table 3 .

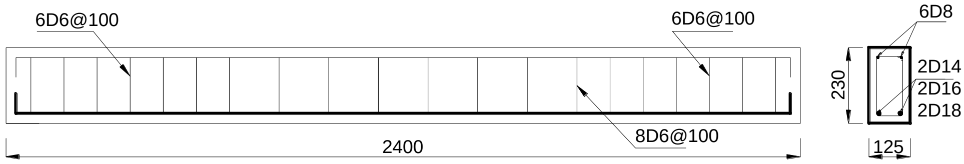

Figure 4 . *Detailing of 9 beam specimens (dimensions in mm)*

__Table 4.__ The steel parameters for beam fabrication

Beam group	No. of sample	Tension rebars	Compression rebars	A_s (mm^2)	A'_s (mm^2)	f_y (MPa)	f'_y (MPa)	E_s (Mpa)
D_14	3	2Φ14	2Φ8	308	100	400	300	200000
D_16	3	2Φ16	2Φ8	402	100	400	300	200000
D_18	3	2Φ18	2Φ8	509	100	400	300	200000

The fabricated beams will be loaded in the 4-point bending test model forces to determine the flexural strength as shown in figures 5, 6.

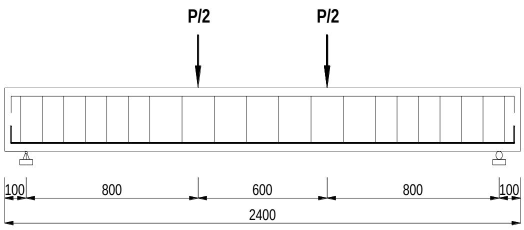

***Figure 5.** Test setup (dimensions in mm)*

***Figure 6.** Flexural test setup for beams*

3.3. Moment - curvature diagram of cross sections of the test beams

Curvature of the beam section is calculated from strains of tensile reinforcement in the test beams. The bending moment at midspan cross section is calculated from loads acting on the beam. Synchronized over time, the moment - curvature diagram of midspan section of the test beams are shown in figure 7, 8, 9.

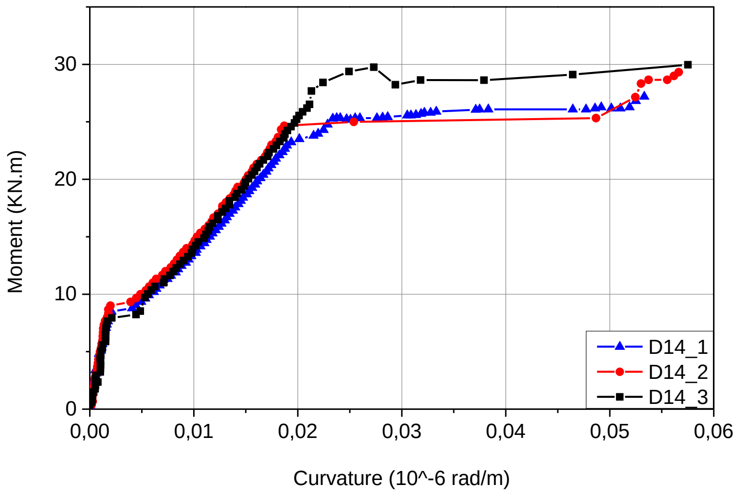

***Figure 7.** Moment - Curvature diagrams of mid-span sections D14 beams*

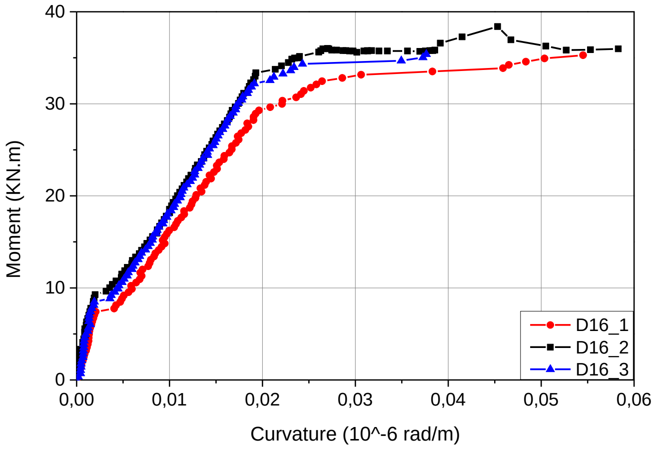

Figure 8. *Moment - Curvature diagrams of mid-span sections D16 beams*

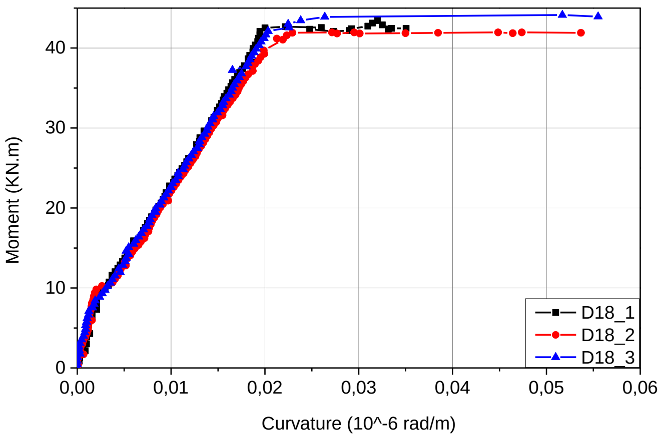

Figure 9. *Moment - Curvature diagrams of mid-span sections D18 beams*

Based on the moment - curvature diagrams of the test beams, the average moment – curvature diagrams of the beam group can be shown in figure 10.

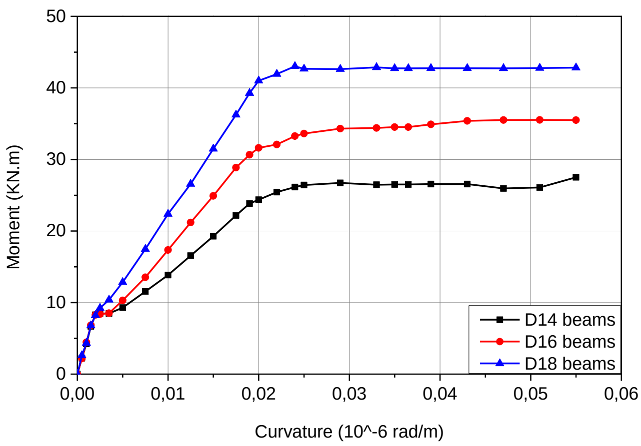

Figure 10. *Average moment - curvature diagrams of mid-span sections of the test beams*

Based on the experiment results some comments can be drawn as follows:

- All three groups of beams with different tensile steel ratios exhibited three relatively similar stages based on the slope of the M - φ curve.
- The relationship M -φ is linear before the first crack appears.
- In the crack formation stage, the moment value does not increase while the deformation increases rapidly until the crack develops.
- In the development stage of cracks, the M - φ curve still shows its linearity. The slope of the chart also decreases due to the lower stiffness caused by cracking.
- The yield point on the diagram is also clear. At this stage, the load increases slowly but the displacement increases very rapidly, indicating the yielding of reinforcement.
- At the failure state, experiment results show that the moment does not increase significantly while the curvature increases rapidly until failure.
- The steel ratio does not affect the cracking moment, but considerably the yield moment and failure moment.

Thus the deformation of the cross section at maximum bending moment has a decisive influence on the ductility of the cross section. The reinforcing steel ratio also significantly affects the ductility of the cross section as shown in the section below.

3.4. Influences of steel ratio on the section ductility of RGPC beams

The mechanical ratio of tensile reinforcing steel of the test beam section is calculated by the formula:

$$\omega = \frac{A_s}{b.d} \cdot \frac{f_y}{f_c^{'}} \quad (7)$$

in which: A_s - area of tension rebar in the beam section; b - width of the beam section; d - distance from the most compressive fibre to the centroid of the tension steel; f_y - yield strength of steel; $f_c^{'}$ - characteristic compressive strength of fly ash geopolymer concrete used in the experiment.

The calculated curvatures of beam sections at yielding of steel and ultimate load are shown in table 5.

Table 5. *Test results of ductility index of beam specimens*

Beam group	ω	Yield curvature φ_y^{ex}	Curvature at ultimate load φ_u^{ex}	Ductility index u
D14_1		0,02015	0,05332	2,65
D14_2	0,122	0,01871	0,05664	3,03
D14_3		0,02013	0,05753	2,86
D16_1		0,02520	0,05451	2,16
D16_2	0,159	0,01922	0,04531	2,36
D16_3		0,01914	0,03764	1,97
D18_1		0,01821	0,03200	1,76
D18_2	0,201	0,02191	0,04485	2,05
D18_3		0,02248	0,05170	2,30

The influences of tensile reinforcement ratio on the ductility index of the test beams are shown in figure 11.

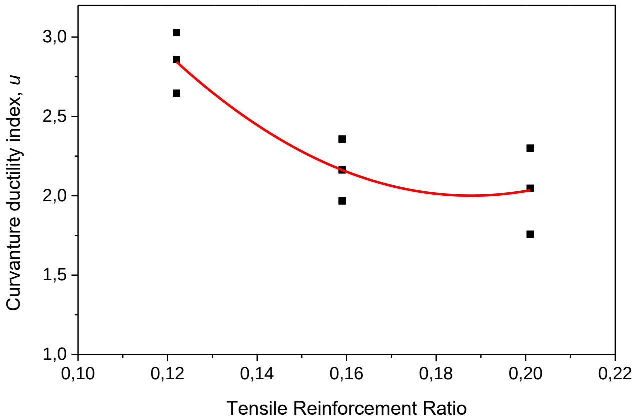

Figure 11. *Influence of tensile reinforcement ratio on the ductility index of the test beams*

The experiment results show that the ductility index of the test beams decreases as the reinforcement steel ratio increases. This is because the ductility index of the beam depends on the strain of the reinforcement after yielding. Higher ratio of tensile reinforcement will reduce the plastic strain of the reinforcement, thus reducing the ductility index of the cross section.

These results are similar to the research of Sumajouw and Rangan studies on fly ash reinforced geopolymer girders [12] and R.F. Warner's research on reinforced concrete girders [9].

IV. CONCLUSIONS

Research on the structural behaviour in general and ductility of GPC in particular contributes to the use of GPC as a common material in construction. This article presents the experimental results of the section deformation and ductility of RGPC beams, in which structural behaviour of RGPC section and influences on section ductility of RGPC beams are compared with that of traditional reinforced concrete beams, in which the ratio of reinforcing steel has a significant influence. Further research needs to be done on the ductility of the RGPC components, which has a decisive influence on the redistribution of internal forces in redundant RGPC structures.

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III. CONCLUSION

This research developed a new type of TRC-LC sandwich beams. The main purpose of the study was to determine the flexural performance of sandwich beams, with different textile reinforcement ratio and depth of beam. The results show that, the adhesion performance was sufficient enough to safely transfer tensile loads from the TRC layer to the LC core. The durable bond between the core and face layers was achieved without any shear connector device. The ultimate loads of the sandwich beams were reached when one of the vertical flexural cracks turned suddenly and developed widely through the LC core. The failure of all the specimens occurred due to tensile break of textile reinforcements, along with the development of critical cracks. Thus, the textile reinforcement ratio increases, the stiffness and strength of sandwich beams also increase. Besides, the stiffness of sandwich panel is affected by the depth of the beams. The stiffness will increase significantly when the thickness of LC core increases.

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