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Research Article

Numerical analysis of flexural and shear behaviors of geopolymer concrete beams

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ABSTRACT

Geopolymer concrete (GPC) is obtained by activating industrial wastes such as fly ash with chemical liquids such as sodium hydroxide (NaOH) and sodium silicate ($Na_2 SiO_3$). In order to use environmentally friendly GPC obtained from industrial wastes instead of Portland cement concrete (OPC), its behavior in structural elements is important and should be investigated in detail. Load-displacement characteristics, flexural and shear stiffnesses, and crack development of samples were obtained by numerical analysis. The GPC beams to be an alternative to OPC beams, their mechanical properties and fracture modes must be at least as much as OPC. As a result of the analyses, it was determined that the 110x20x15 cm GPC beams with compression reinforcements of 2Φ8 and tension reinforcements of 2Φ8, 3Φ14 and 2Φ18, respectively, showed similar flexural, shear and crack development with OPC beams. Simulations of GPC beams were made up to the breaking point, contributing to understanding its behavior. The ultimate load for both OPC and GPC beams in the FEM model was 45 MPa, while in the experimental model, the OPCB was 55 MPa and the GPCB was 60 MPa. While the first crack started at 1 mm in the OPCB-FEM model, the GPCB-FEM model showed a more elastic behavior, and the first crack started after 3.5 mm displacement. The load-displacement results for 2Φ8 compression and 3Φ14 tensile reinforced beams contain closer results in FEM and experimental. The ultimate load states are between 160 MPa and 180 MPa, but the maximum strengths of OPCBs are slightly higher. After 7.5 mm, crack formation continued to increase. Maximum strength in beams with 2Φ8 pressure and 2Φ18 reinforcement is in the range of 175–185 MPa. Although the values are very close to each other, it seems that they did not exceed the strengths of the previous 3Φ14 reinforced beams. On the other hand, it is seen that the plastic deformation of GPCBs starts from 7.5 mm, while OPCBs start after 10 mm. Observing the load-displacement graphs and the mobility of concrete and reinforcement, it can be said that the yield in the steel reinforcement and the crack development in the beams are simultaneous, and the crack development in GPCs starts a little earlier than the yield of the steel reinforcement.

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1. INTRODUCTION

While modern building constructions continue worldwide, limestone calcination and carbon dioxide emissions caused by cement production, which is the primary concrete binding material, are considered the main causes of global warming. While humanity is looking for solutions to the world's climate crisis, scientists in civil engineering are working on an alternative to cementitious concrete and a more environmentally friendly concrete. Geopolymer Concrete (GPC), obtained by activating more environmentally friendly materials, has recently attracted great interest as an alternative to cementitious concrete. GPC is obtained by adding fly ash obtained as waste from the chimney of thermal power plants to coarse and fine aggregates and activating them with chemicals such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). A lot of work has been done on the material properties, microstructure and compositions of GPC, which has not yet found application in practice. Research on the mechanical properties of GPCs remains more limited. From this point of view, the flexural and shear behavior of Geopolymer beams (GPCB) is among the important research topics. The structural behavior of GPCBs has been observed with experimental and numerical studies by Pham et al. (2021) [1]. Considering the linear elastic behavior of GPCs, flexural cracking and steel yielding, they revealed that GPCBs behave ductility. In addition, both experimental and numerical analysis results confirmed that the moment capacity increased when the steel reinforcement ratio increased. Hutagi et al. (2011) [2] studied the flexural behavior of GPC and Portland Cement concrete beams (OPCBs). As a result of the study, they revealed that the post-peak ductility of GPCBs is lower than that of OPC beams, while GPCBs behave in the same way as OPCBs in terms of load-deflection properties, cracking moment and service load moment. A similar statement in Kumar and Kumar (2016) found that the load deviation properties of OPCBs and GPCBs are almost the same. The cracking moment of GPCB was lower compared to OPCB [3]. However, the observed crack patterns and fracture modes for GPCBs were like OPCBs. The total number of felaxural cracks was nearly the same when all beam types were considered. The beams failed as their steel yield first, and then the concrete was crushed at the pressure zone of surface [3], GPCBs the flexural behavior, comparing the numerical simulation and analytic calculations OPCBs, concluded that they were more stringent than the theoretical calculation of GPCBs flexural behavior. In addition to the experimental investigation, they also performed numerical studies using ABAQUS finite element software to investigate the structural behavior of GPCBs [4]. Amiri et al. (2016) [5] examined the structural behavior of GPCBs in their study with the finite element method. They found that the experimental deviations differed from the ABAQUS simulations due to friction forces and sliding behavior at the beam-support contact. Uma et al. (2012) [6] tried to model the structural behavior of GPCBs using ANSYS 12.0 software. The authors showed a 20% difference between the experimental and numerical results in this comparative study.

There is little research to evaluate the shear behavior, crack shapes, and failure modes of reinforced GPCBs under bending load. Therefore, studies on the shear behavior of GPCBs are precious. Yost et al. [7] found that shear force transfer and shear strength were similar in both geopolymer and cement-based concrete beams. Yacob et al. [8] four GPCBs and one OPCB presented beams' strength, strains, deformations, and failure modes in their experimental study to determine shear strength. As a result of the research, it was found that the parameters that affect the shear strength of OPCBs, namely shear reinforcement, w/v and concrete compressive strength, also affect the shear strength of GPCBs. GPCB showed almost the same ductility behavior as OPCB with similar reinforcement in load-deflection response. Shear deformation and mean strain were more critical in beams that excel in shear and torsion-shear, while they were less important in beams that excel in shear-flexural. Visintin et al. [9] presented the low-level test results of eight reinforced concrete GPC beams without stirrups, along with the results of four direct shear tests. They determined that the shear friction properties for the GPC used in the experimental research were within the range of the shear friction properties of the OPC concrete. On the other hand, Mourougane et al. (2012) [10] observed that GPCBs showed higher shear strength in the range of 5–23% compared to OPCBs. However, Mourougane et al. [10] found that ACI 318 [11] gave a good estimate of the shear strength of GPCBs, with an average test prediction ratio of 0.96. Chang (2009) [12], based on research on GPCBs with varying longitudinal and transverse reinforcement ratios, that the calculation method for OPCBs is AS 3600 [13] and ACI318 [11], giving average test-to-estimate ratios of 1.70 and 2.55, respectively. They stated that GPCBs could be safely used to predict the shear strength of GPCBs. Ng et al. [14] found that shear cracking was delayed when steel fibers were added to GPC, but finer cracks were formed. It has been found that the crack width is reduced when smaller diameter straight steel fibers are used. As a result, steel fibers proved to increase the cracking load and ultimate strength of GPCBs.

Today, simulation of structural elements in computers with FEM plays a growing role in civil engineering studies. This software produces approximate solutions by making predictions and providing analysis. Comparably, FEM analysis yields 90% to 95% accurate results in analysis modes [15, 16]. Although the shear behavior of the beam provides the correct properties of the structure, the expense and time

Table 1. Beam geometry and reinforcement information

Group	Sample name	Beam dimensions (mm)	Reinforcement steel		Stirrup
			Pressure steel	Tension steel	
1	OPC1	150x200x1100	*2Φ8*	*2Φ8*	*Φ8/150*
	OPC2	150x200x1100	*2Φ8*	*3Φ14*	*Φ8/150*
	OPC3	150x200x1100	*2Φ8*	*2Φ18*	*Φ8/150*
2	GPC1	150x200x1100	2Φ8	2Φ8	Φ8/150
	GPC2	150x200x1100	*2Φ8*	*3Φ14*	*Φ8/150*
	GPC3	150x200x1100	*2Φ8*	*2Φ18*	*Φ8/150*

consumption during the experimental calibration are disadvantageous [17]. The results obtained from the ANSYS software, which digitally models the beam experiments, entirely depend on the mesh size, material properties, and load increases [18]. Rajhgopal et al. [19] modelled the concrete as a 3D solid65 element and the reinforcement as a Link 8 element for GPC beam via ANSYS software. As a result of nonlinear FEM analysis of geopolymer beams, load-deflection characteristics, fracture modes and crack states were observed together with experimental results. Modeling GPCBs that exhibit nonlinear behavior until failure with FEM reduces costs and produces results faster than laboratory testing. GPC preparation of concrete as environmentally friendly concrete still has many difficulties compared to casting and testing OPC concrete. Said beam denier is even more difficult. There are many experimental and FEM analysis studies on OPCBs and steel beams [20–30], but the study on GPC is very limited. Thanks to this study, the analysis of GPC beams in terms of both flexural and shear behavior is considered an innovation.

Most of the studies on GPCs are related to the microstructure and chemical composition of GPCs. However, studies on the structural behavior of GPCB still remain limited [7–10, 12, 31]. Examination of the real-time behavior of beams produced from GPC, obtained from strain and stretching in the laboratory environment, can be quite a time consuming, and materials can be quite expensive. To contribute to this limited area, ANSYS, finite element-based computer software with which nonlinear beam models can be defined easily due to its cost-effectiveness, was used in this study. This study aims to examine geopolymer concrete beams' flexural and shear behavior in various crack conditions such as crack initiation, propagation, flexural strength, load-deflection and structural failure modes using three-dimensional FEM analysis. At the same time, it is to reveal the time-dependent comprehensive behavior of the beam under the influence of increasing load until the moment of fracture under the critical distribution of stresses and effective strains in the steel reinforcement by comparing it with the results obtained from the calculations in the laboratory environment. Using software that performs finite element analysis makes it possible to simulate GPCBs up to the moment of fracture. This study aims to contribute significantly to the future development of this environmentally friendly concrete.

2. MATERIAL AND METHOD

2.1. FEM Development of GPC Beams

Observation of flexural and shear behavior of GPCBs was performed numerically with ANSYS Workbench (21.2) software. First, beams with a width of 150 mm, a height of 200 mm and a length of 1100 mm were drawn with AutoCad software, then ANSYS Workbench software was used in usable format. 2Φ8 longitudinal reinforcement is placed in the compression zone of all beams. The transverse reinforcement is adjusted to be 8Φ8/150 mm in each beam. In the research, a total of 6 beams were modeled and analyzed by using three different GPC and OPC beams matched with each other. The transverse reinforcements are sized so that the cover is 25 mm. The cross-section and reinforcement information of the modeled reinforced concrete samples are given in Table 1, and the longitudinal and transverse reinforcements placement are given in Figure 1.

According to the previous experimental study results for the concrete block, mechanical definitions were made in ANSYS. SOLID65-3D element is used while defining the concrete in ANSYS Workbench finite element model. SOLID65 is widely used for 3D concrete modeling of reinforced solids. The special cracking and crushing abilities of reinforced concrete elements, resembling a 3D structural solid, are very well represented by SOLD65. Thanks to this element, nonlinear material properties are defined and processed quite successfully. It can crack (in three vertical directions), crush, cause plastic deformation and creep into concrete. SOLD65 geopolymer is suitable for simulating the cracking behavior of concrete in the tensile zones (bottom) as well as the nonlinear performance of the concrete material in three orthogonal directions, such as crushing in the compression zones (top) by processing [32]. Rebar has to ability to tensile and compress but not cut. The LINK 180 element type used for modeling vertical and horizontal steel bars from the ANSYS 21.2 element library facilitates linear and nonlinear deformation in its

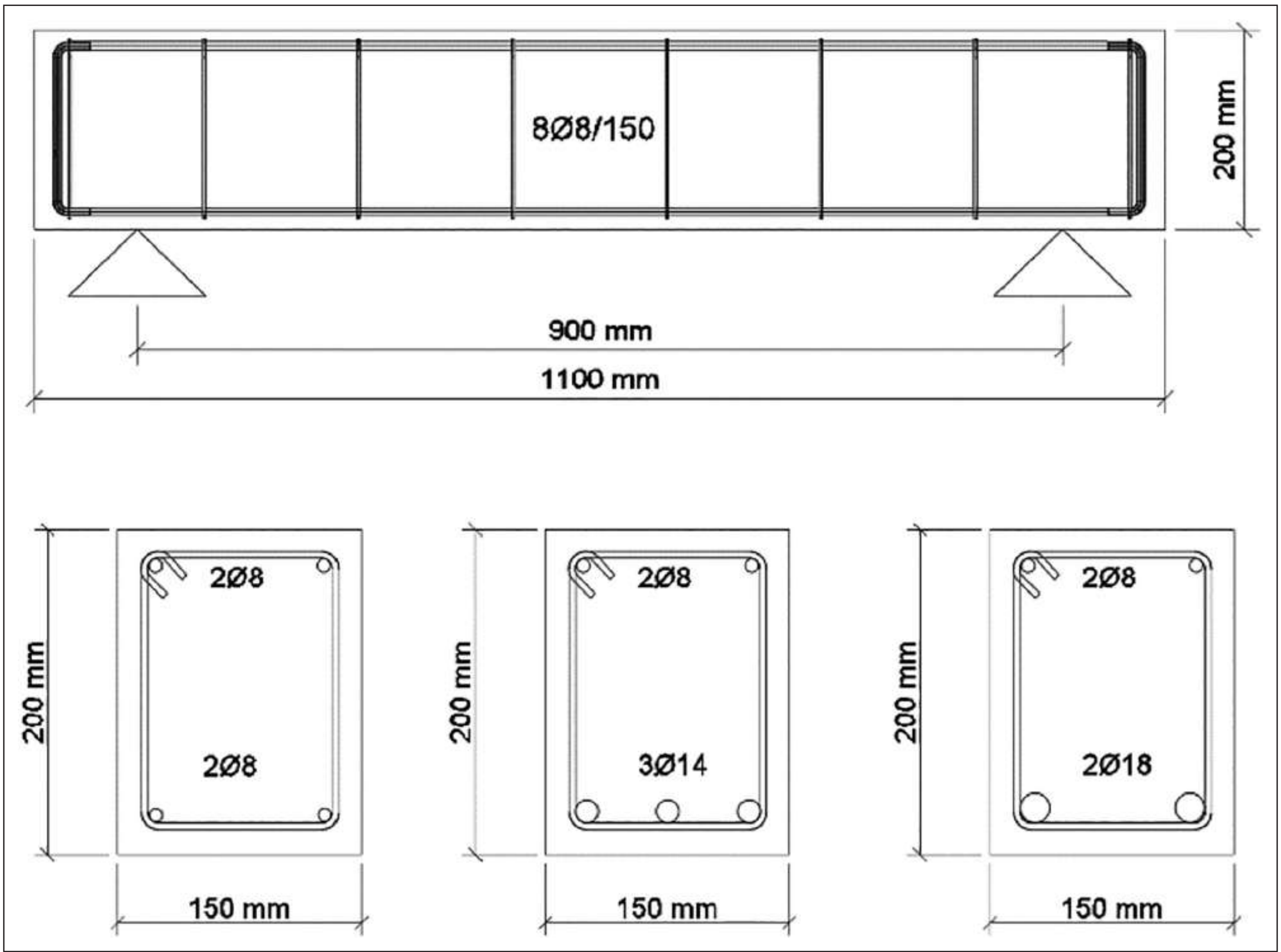

Figure 1. Beam sections and reinforcement placement.

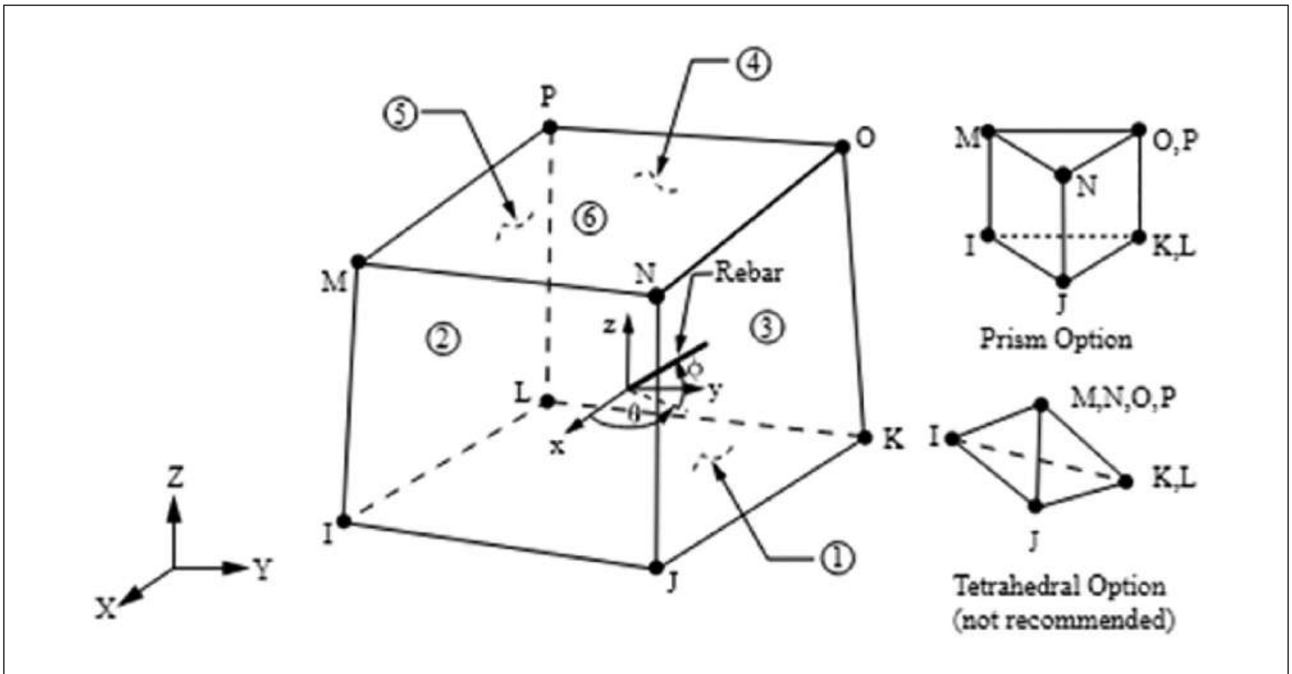

Figure 2. SOLID65 geometry.

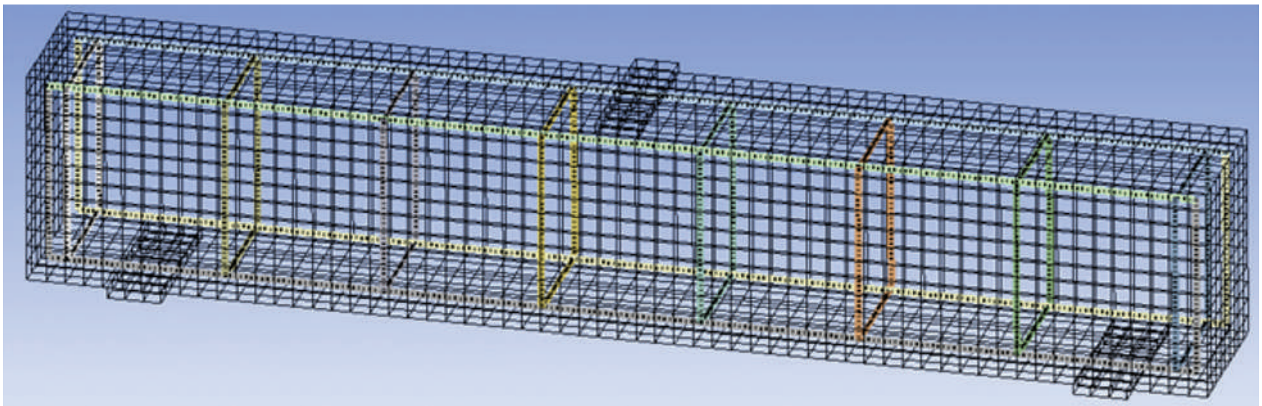

Figure 3. Reinforced Concrete Beam finite element mesh model.

Table 2. Reinforcement properties in axial tension

Rebar diameter (mm)	f_y (MPa)	f_u (MPa)	Elongation (%)	f_u/f_y
8	424	541	37.5	1.27
14	453	572	32.8	1.26
18	456	564	24.4	1.24

f_y: Yield strength; f_u: Tensile strength.

Table 3. Analytically results of flexural and shear load

Sample code	Longitudinal reinforcement	Beam flexural load capacity (kN)	Beam shear load capacity (kN)
(GPC-OPC) 1	2Φ8	27.35	119.5
(GPC-OPC) 2	3Φ14	106.3	119.5
(GPC-OPC) 3	2Φ18	114.3	119.5

plane. The described solid model can crack in tension and crush in compression. Each element of the SOLD65 that defines the concrete is represented by eight nodes with three degrees of freedom at each node: the nodes express the translations in the x, y, and z directions. The geometry, node positions and coordinate system for this element are shown in Figure 2 in SOLID65 geometry [33].

Inserted into the geometry defined as SOLID 65, With the commands, the mechanical properties previously determined by the experimental method were defined separately for GPC.

MPTEMP,,,,,,,
MPTEMP,1.0
MPDATA,EX,solid65_matid ,,16972
MPDATA,PRXY,solid65_matid ,,0.24
and for OPC
MPDATA,EX,solid65_matid ,,25256
MPDATA,PRXY,solid65_matid ,,0.2

The concrete body of the OPC beam is meshed with 18 mm and the reinforcements with 5 mm. It consists of a total of 12,252 nodes and 8681 elements. The transparent view of the finite element mesh model of the concrete body, reinforcement and support elements is shown in Figure 3.

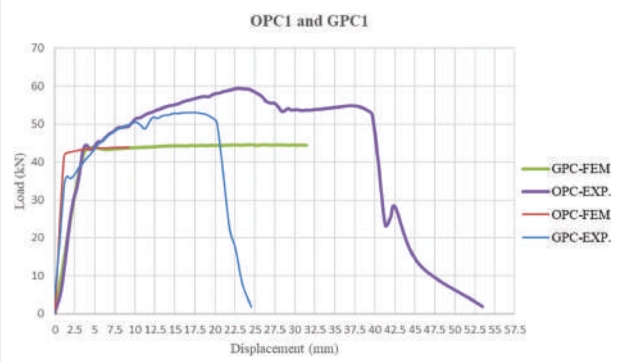

Figure 4. Stress-strain curves (OPC and GPC 8 mm).

The mechanical properties of steel reinforcement bars were determined due to the tensile test in the Kayseri University Tomarza Vocational School Construction laboratory. Then, definitions were made in ANSYS according to the results obtained. Values such as yield strength, tensile strength and elongation at break of longitudinal and transverse steel reinforcements defined while modeling in ANSYS Workbench are as in Table 2.

3. RESULTS AND DISCUSSION

In the beams used in the experimental study, flexural and shear behavior were investigated for three different longitudinal reinforcement ratios. In the analytical calculations, the shear bearing capacity of all beams is higher than the flexural bearing capacity. However, in beams 2 and 3, shear and flexural strengths are very close. Therefore, the expected failure of the beams is flexural in the first beam and flexural and shearing in the second and third beams, in the form of oblique shear failure. With

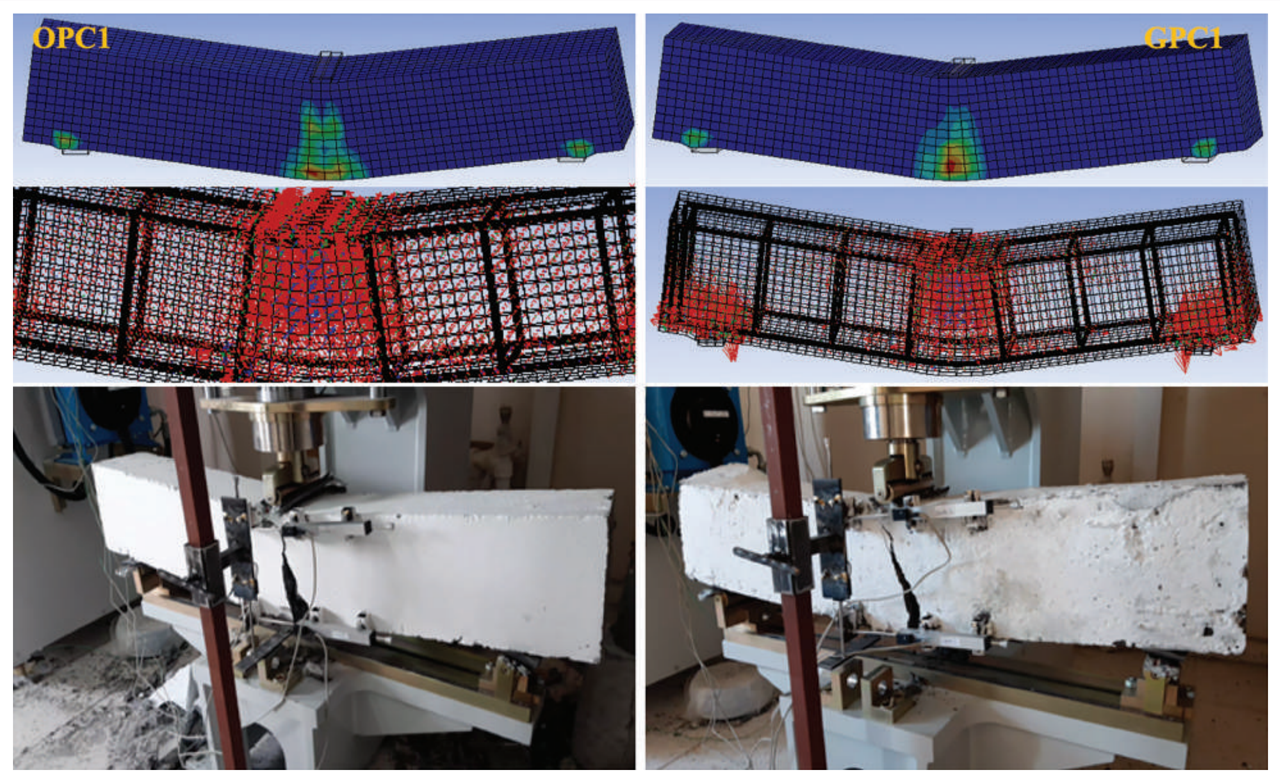

Figure 5. OPC and GPC beam flexural behavior (8 mm).

this aspect, both shear and shear behavior can be considered in the article. As stated in the title of the manuscript, the study aims to determine the shear and flexural behavior of geopolymer beams. In case the concrete strength is 30 MPa, analytically calculated flexural and shear load capacities are given in Table 3.

As a result, the flexural strength of all beams is lower than the shear strength. However, for the two samples, due to the flexural and shear strengths being close, the fractures occurred in a way that included both behavioral effects.

3.1. Material Test Results

According to the experimental study, the beams modeled with ANSYS Workbench were loaded with 50 mm displacement from a single point in the middle and analyses were carried out. Stress-strain curve, crack states and load-deflection graphs obtained as a result of simulations are presented in this section and comments are made on them.

3.2. Findings from Beams

The load-displacement graphs of OPC and GPC beams with 2Φ8 mm compression and tension reinforcement, which were analyzed numerically, are shown in Figure 4 compared to the previous experimental results. In the analysis made with the FEM model, the yield region is approximately the same as in the experimental model. There may be significant differences between the experimental study

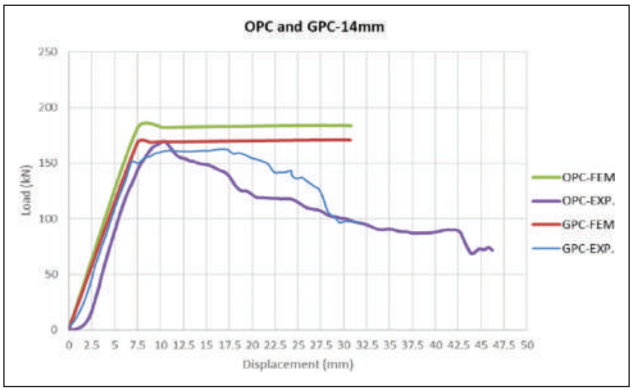

Figure 6. Stress strain curves (OPC and GPC 14 mm).

results and the FEM model. But it is an important result to reveal the yield strength limit, which is the end of the elastic behavior and the starting point of the plastic behavior, in the stress-strain curve. Although the graphical results obtained within the scope of this study do not match exactly with the experimental results, the yield strength points are approximated. With the development of the ANSYS finite element method, it will be possible to obtain results close to the experimental model over time.

The analysis images using the simply supported OPC and GPC FEM model under vertical load are shown in Figure 4. The final load for both OPC and GPC in the FEM model was 45 MPa, while in the experimental mod-

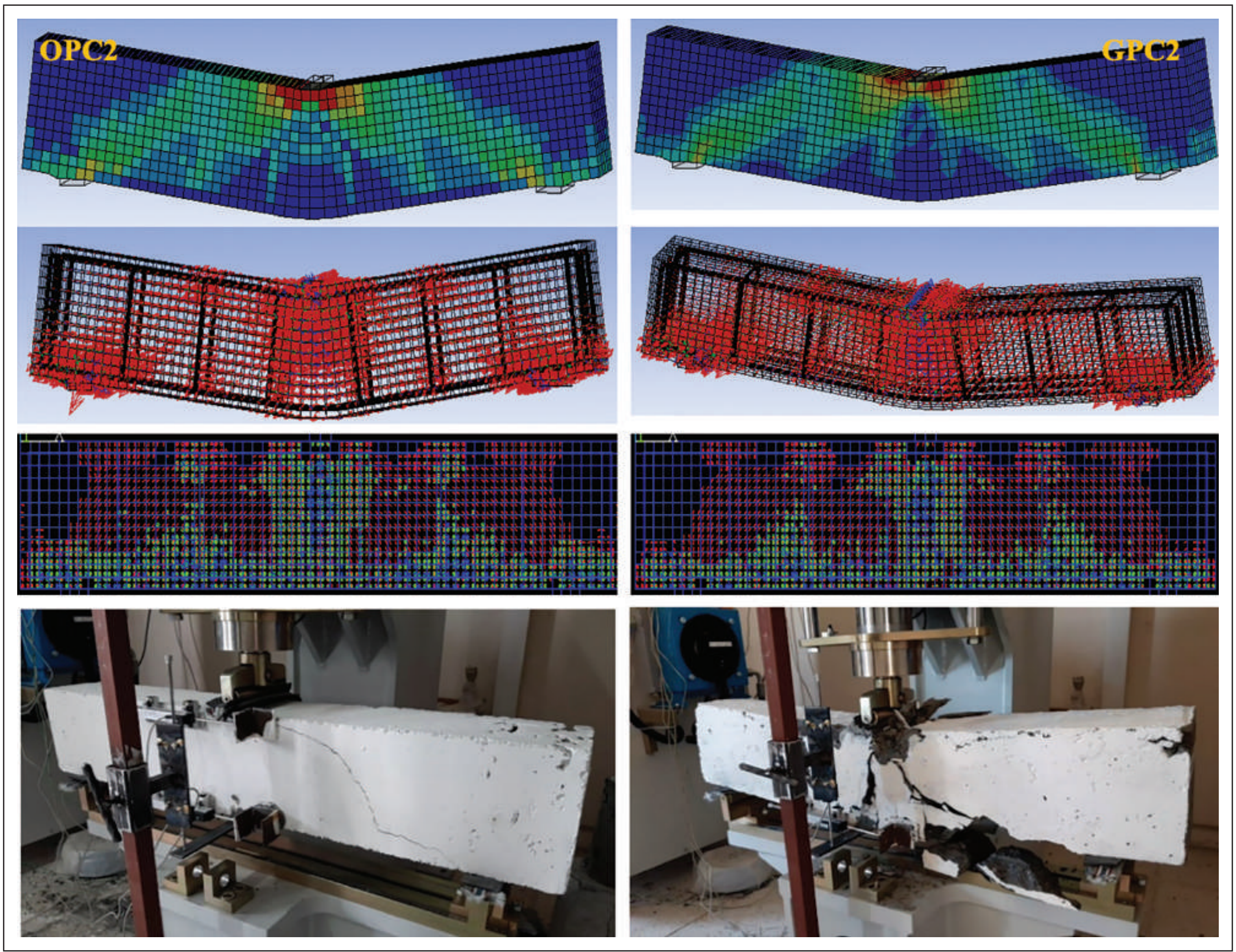

Figure 7. Stress strain states (OPC and GPC 14 mm).

el, the OPC was 55 MPa and the GPC 60 MPa. While the first crack started at 1 mm in the OPC-FEM model, the GPC-FEM model showed a more elastic behavior, and the first crack started after 3.5 mm displacement. In the experimental model, the opposite is the case; crack formation started after 1 mm displacement in GPC, whereas crack formation started after 3.5 mm in OPC. When the yield boundary states are observed in FEM and experimentally, progressively increasing cracks in the middle reveal the flexural behavior. Flexural cracks started in the lower part of the beam and gradually increased due to the increasing tensile load. The red-colored regions in Figure 5 clearly show the stress states and cracks pattern. The stress, strain and flexural cracks occurring in the middle of the beam are similar for GPC and OPC and prove the experimental images at the bottom.

It can be said that the graph in Figure 6 shows that the FEM and experimental results of beams with 2Φ8 compression and 3Φ14 tension reinforcement are more compatible. The FEM results were slightly above expectations for both OPC and GPC. The ultimate load states are between 160 MPa and 180 MPa, although the maximum strengths of OPCs are slightly higher. After 7.5 mm, crack formation continued to increase. In their study, Venkatachalam et al. [32] stated that crack formation in-

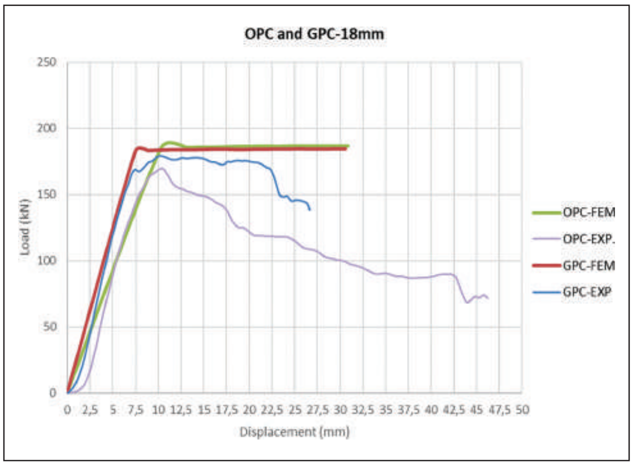

Figure 8. Stress-strain curves (OPC and GPC 18 mm).

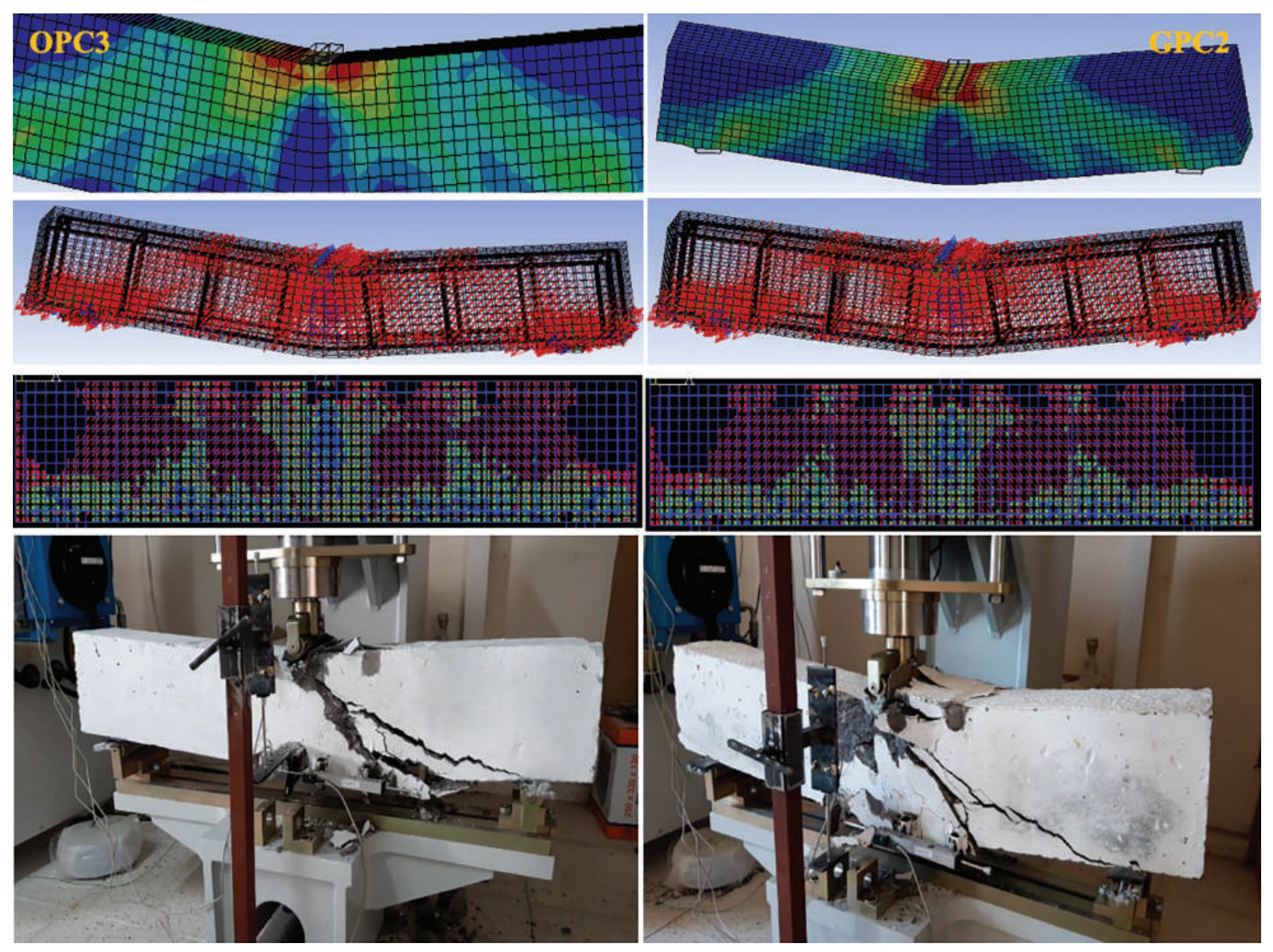

Figure 9. Stress-strain states (OPC and GPC 18 mm).

creased after 7.5 mm in the test of 1500 mm long beam with 8 mm shear and 10 mm flexural reinforcement. But, they stated that excessive flexural stress and cracks occur in the middle region of the beam [21].

It is seen that the flexural performances of OPC and GPC beams with 3Φ14 mm reinforcement in the tension region are excellent (Fig. 7). Especially in the FEM model, crack formations can be seen very well; OPC and GPC also show similarities. Cracks mainly formed towards the support points in the shear region, which confirms the experimental images.

Maximum strength in beams with 2Φ18 compression and 2Φ18 tension reinforcement is in the range of 175–185 MPa. Although the values are very close to each other, it seems that they did not exceed the strengths of the previous 3Φ14 reinforced beams. According to the FEM and experimental curve in Figure 8, the linear behavior of the beams appears to be coincident. On the other hand, while the plastic deformation of GPCs started at 7.5 mm, it was seen that OPCs started after 10 mm.

In Figure 9, crack formation is observed in accordance with the experimental result with the FEM model. The cracks formed are mostly in the shear region. While excessive stress is seen around the force application point in the compression region, less stress is seen in the tensile region. With the increase in longitudinal reinforcement, the flexural strength of both OPCs and GPCs increases, while crack formation in the shear region shows similarities.

When the load-displacement graphs and the mobility of concrete and reinforcement are observed. It can be said that the yield in the steel reinforcement and the crack development in the beams are simultaneous. However, it can be said that crack development in GPCBs starts a little earlier than in steel reinforcement. Figure 10 shows the stress and plastic deformation of the tensile and compressive reinforcement of the reinforcements in the GPC beams. Tensile and compressive reinforcements are equal in Figure 10a. In the beam, which is designed as 2Φ8, stresses also occur in the pressure bars. It is observed that the tensile reinforcement of the beam is designed as Figure 10b. 3Φ14 works well, and the compressive reinforcement has less stress. It is observed in Figure 10c. 2Φ18 that the tension reinforcement works well and the compressive reinforcement remains more rigid.

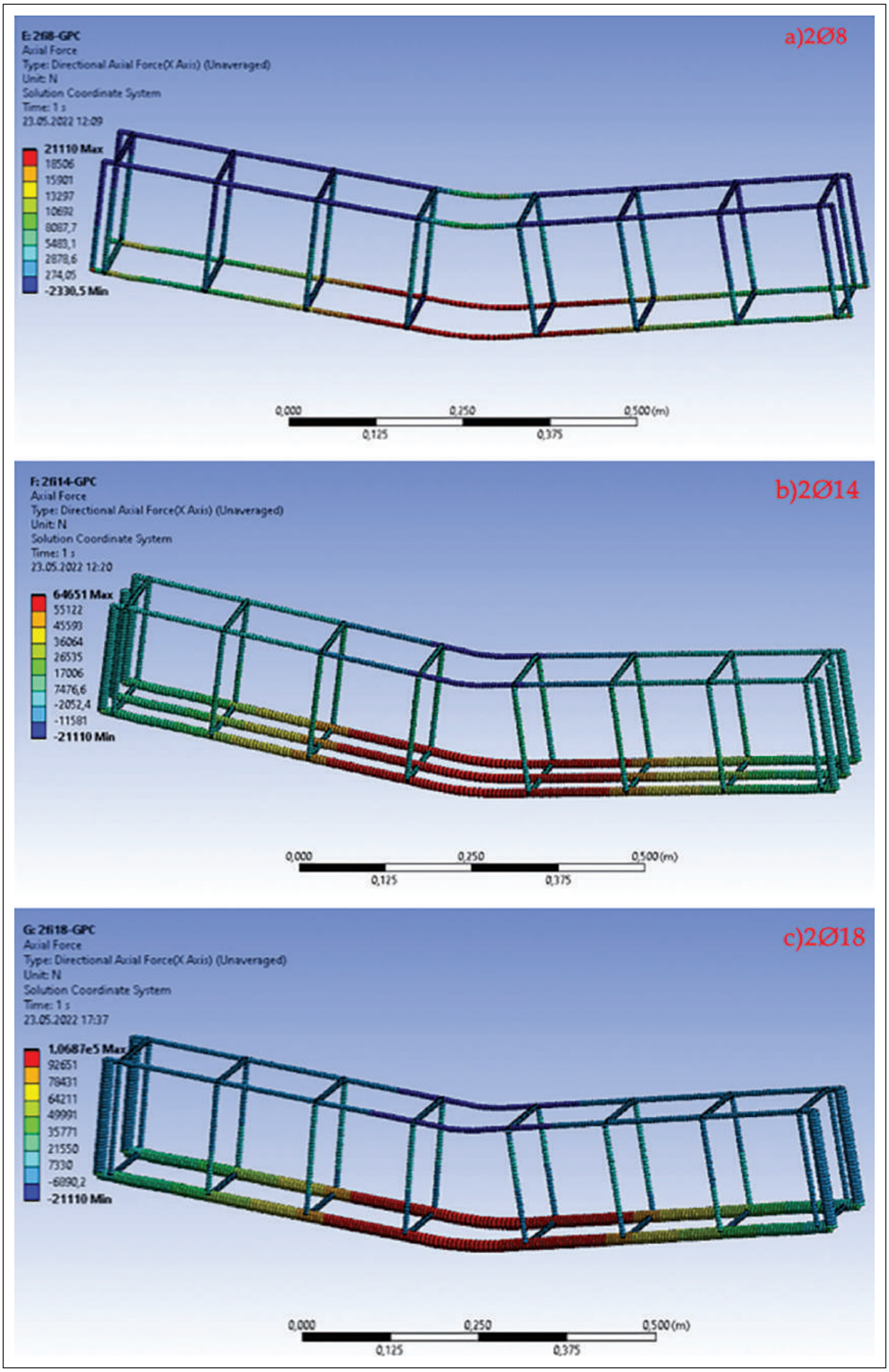

Figure 10. Elastic and Plastic behaviour of steel reinforcement.

4. CONCLUSION

As a result of GPC beam analysis via ANSYS Workbench, it gave similar values to the analysis of OPC beams. The results yielded from the numerical study are consistent with the previous experimental study results, showing that the investigation is reliable. The significant findings and results obtained as a result of the study are as follows. This study yielded results consistent with other studies in the literature.

- In the beams with 2Φ8 compression and tensile reinforcement, flexural cracks were formed mostly in the middle region up to the bottom of the beam. In the FEM model, the final load for both OPC and GPC beams was very close, while the last load derived from the experimental results of OPCBs was higher than the GPCBs with 0.9%. While the first crack started at 1 mm in the OPCB-FEM model, the GPCB-FEM model showed a more elastic behavior, and the first crack started after 3.5 mm displacement. In the experimental model, the opposite is the case; crack formation started after 1 mm displacement in GPCB, whereas crack formation started after 3.5 mm in OPCB.
- The load-displacement results for 2Φ8 compression and 3Φ14 tensile reinforced beams contain closer results in FEM and experimental. The ultimate load difference between the two beams is approximately 12%, but the maximum strengths of OPCBs are slightly higher. After 7.5 mm, crack formation continued to increase.
- The maximum strength difference in beams with 2Φ8 pressure and 2Φ18 reinforcement is around 0.57%. Although the values are very close to each other, it seems that they did not exceed the strengths of the previous 3Φ14 reinforced beams. On the other hand, it is seen that the plastic deformation of GPCBs starts from 7.5 mm, while OPCBs start after 10 mm. Observing the load-displacement graphs and the mobility of concrete and reinforcement, it can be said that the yield in the steel reinforcement and the crack development in the beams are simultaneous, and the crack development in GPCs starts a little earlier than the yield of the steel reinforcement.
- Since the mechanical behavior of GPCBs shows similar behavior to OPCBs. This study, which will be an essential reference in terms of supporting experimental studies and conducting theoretical studies quickly, that GPCBs analysis can be easily done with the FEM model.
- Finally, simulations of Geopolymer concrete beams were made up to the moment of fracture and it was tried to contribute to the understanding of the behavior of this environmentally friendly concrete under flexural.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

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PEER-REVIEW

Externally peer-reviewed.

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