and slabs) responsible for the integrity of an entire structure. Thus, examination of crack and flexural behaviour of these bearing elements is very important for the evaluation of safety and future of concrete buildings. In the past, many investigators were investigated the crack and flexural behaviour of concrete beams using includes local deformation measurements with strain sensors and 3D modelling.

Some of these studies are explained in detail in this section. The experimental results of two concrete continuous beams reinforced with either steel or GFRP bars as reference beams were reported in literature. That study showed the load capacity prediction, for hybrid reinforced concrete continuous beams based on a collapse mechanism with plastic hinges at mid-span and central support sections, is reasonably close to the experimental failure load (Araba and Ashour 2018). Likewise, the results of an experimental study designed to investigate the combined effects of corrosion and sustained loads on the structural performance of reinforced concrete beams were published previously. The results showed reinforcement corrosion had no obvious effect on the transverse crack spacing and a slight effect on the development of transverse crack width for the beams under simultaneous loading and corrosion (Zhang et al. 2018). In addition to these studies, contributions of the strengthening/repair of slender reinforced concrete beams subjected to bending by applying the TRC composite were assessed. The mechanical performance of TRC in strengthening/repair of the reinforced concrete beams analyzed considering load/deflection, failure mode, flexural rigidity, deformation of steel, pattern cracking, the crack opening (Truonga et al. 2017). Additionally, one of these studies was focused on the relationship between the shear capacity and the flexural cracking load of Fiber Reinforced Polymer (FRP) reinforced concrete beams without stirrups. A relationship between the cracking load that causes a beam to crack at the middle of shear span and the shear capacity of the beam is confirmed based on the test results of 29 beams (Alam and Hussein 2017). An existing average moment of inertia model and Monte Carlo simulation to take into account the effect of historical cracking damage on the reliability of serviceability calculations for reinforced concrete (RC) members was adopted. The results confirmed that the effect of historical cracking damage on short-term serviceability reliability should be taken into account when the deflection induced by historical loading is larger than the deflection limitation (Xu et al. 2018). Moreover, it was assessed effects of sand content on the workability and mechanical properties of concrete using bottom ash and dredged soil-based artificial lightweight aggregates. A new method was proposed and proposed model indicated that a lower water-to-cement ratio is required with the decrease in the natural sand content to achieve the designed compressive strength of concrete (Lee and Yang 2019). As seen at these works, there are many studies related with experimental tests and numerical analyses of reinforced concrete beams. Moreover, there are many studies about performance of concrete in the literature (Topçu and Bilir 2009, Topçu et al. 2009, Topçu and Bilir 2010, Bilir 2012, Bilir 2016). However, in the literature, very few investigators were examined the effect of %75 bottom ash ratios on the crack and flexural behaviour of reinforced concrete beams. Moreover, there are very few studies about the effect of bottom ash ratio, replacing fine aggregate, on the total weight of concrete structure in the past. Thus, this study provides many significant supports to the literature.

Scope of study

In this study, the effect of %75 bottom ash ratio on the crack and flexural behaviour of reinforced concrete beams (RCBs) is examined and evaluated in detail. This bottom ash ratio is used to replace 0-5 mm grain size aggregates. One of the most important aims of this study is to observe the effects of this bottom ash ratio on the consistency of fresh concrete. Moreover, another aim of this paper is to observe the effect of %75 bottom ash ratio on the flexural behaviour of RCBs. Thus, produced concrete beams were subjected to flexural testing in a fully organized laboratory, and total 20-ton vertical load were applied to RCBs. According to experimental test results, flexures and cracks in the RCBs were examined and shown in detail. In addition, confirming experimental results by 3D numerical analyses was the most significant purpose of this study. For this purpose, 3D finite element models (FEMs) of RCBs were modelled using ANSYS software based on the finite element method. According to numerical analyses, flexures in the 3D models of concrete beams were determined and it was clearly seen these flexures are very close to the experimental cracks.

Experimental set-up

In this section, the experimental test set-up of reinforced concrete beams is expressed in detail. Used devices for crack and flexure analyses of concrete beams are shown in Fig.1. The beams are placed on a pin support at one end and a roller support at the other end. This static situation lets the reinforced concrete beams to deflect under loading (Fig. 1 and Fig. 2). A ±250 mm displacement capacity is used to apply cyclic displacements at the pile top as shown in Fig. 1. Moreover, a force controlled actuator with a 1000 kN load capacity is used to apply axial load on the pile specimens. Accordingly, flexural cracks are measured at critical points where LCF cracks are expected to occur as observed from finite element modeling and analysis of the test set-up. The vertical load exerted and displacements are measured by a TDG-Ai8b model data-logger and stored on a hard-disk connected to the device via computer.

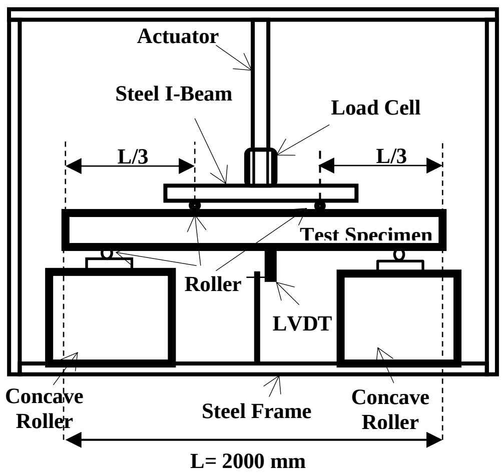

Fig. 1 Loading configuration for static testing.

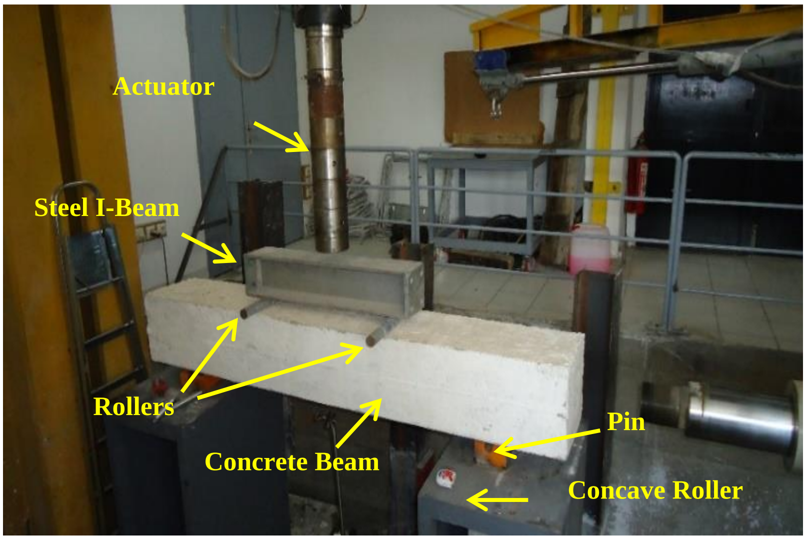

Fig. 2 Static testing apparatus

Experimental results and discussion

In this section, the effect of bottom ash ratio on the flexure behaviour of reinforced concrete beams is clearly seen and evaluated in detail. After 2 various reinforced concrete beams were prepared in the laboratory, these beams were subjected the flexure experiments. These flexures in the beams were assessed in detail and it is clearly seen that each bottom ash ratio had different flexural effects on the concrete beams. Moreover, while performing experiments, various deflections were obtained for each concrete beams. Each beams had different load carrying capacities and these capacities were very important to evaluate the effect of %75 bottom ash ratio on the flexural behaviour of concrete structures. In this study, 2 various concrete beams were tested as seen below (Table 1).

Table 1 Reinforced concrete beams for 2 experimental tests.

Case	Statement
Case 1	Reference concrete beam (0% bottom ash)
Case 2	Adulterated concrete beam (75% bottom ash)

Case 1: Crack and load-deflection behaviour of reference concrete beam under static loading.

According to experimental results, it is observed that there were significant shear and flexural cracks in the reference reinforced concrete beam depending the vertical load. Under vertical pressure, the maximum deflections in the reference concrete beam were measured by LVDT device and these deflections were graphically presented in this section. When examined Fig. 3a is, it is obviously seen that the maximum crack in the beam gap was as 3.96 cm and this crack occurred at 85th second of the experiment. This result gives significant information on how much maximum crack gap can occur for reference concrete beams under vertical loads. Figure 3b also shows serious cracks may occur in concrete beams under strong loads and significant flexural cracks are seen from Fig. 3b. These places of cracks are clearly shown as where vertical cracks can occur in the beam. In addition, the maximum distance between the vertical cracks was as 150 mm in the reference concrete beam (Fig. 3c). According to Fig. 3f, it is understood that the maximum shear cracks start from the place where the load is applied to the beam and they continue to the bottom of beam.

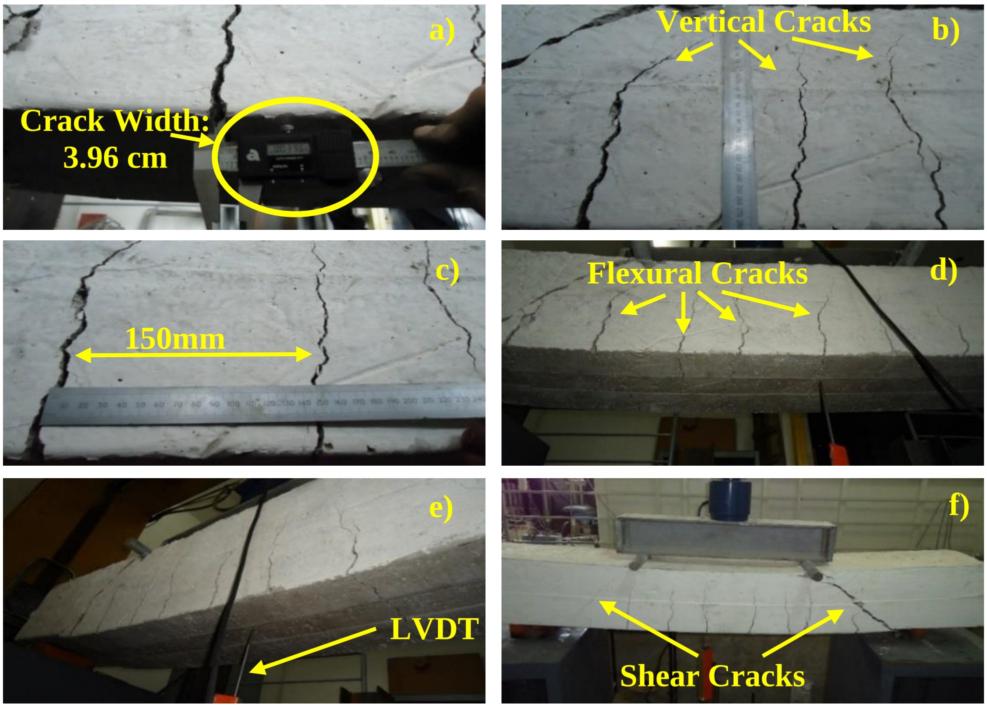

Fig. 3 Crack and flexure behaviour of reference concrete beam.

The LVDT device is placed under the concrete beam during the experiment, and the numerical data about how much deflection occurred in the beam depending vertical loads were obtained. In Fig. 4, load-deflection graphic is seen for reference concrete beam. According to Fig. 4, deflections increased as linear line until a certain time and end of this linear line corresponds to 178.0 kN. However, for more vertical loads than 178.0 kN, deflection line of reference concrete beam is nonlinear. In addition, although load-deflection graphic is linear line between 178.0 kN ile 216.4 kN, after load 216.4 kN, the deflection increases. Then, deflection increases linearly until maximum load (228.9 kN), and 3.74 cm deflection is observed at maximum vertical load. After 228.9 kN, although the load decreased, the deflection is slightly increased. 3.89 cm maximum deflection was observed at end of the experiment and beam lost its load carrying capacity at this deflection value. In other words, the beam can carry 228.9 kN maximum load and maximum 3.89 cm deflection occur in the reference reinforced concrete beam under vertical load. These results clearly indicate many important information about the load carrying capacity of the reference concrete beams.

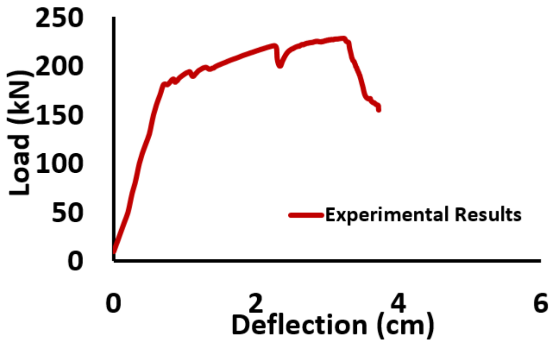

Fig. 4 Load-Deflection behaviour of reference concrete beam under vertical loads.

Case 2: Crack behaviour of 75% bottom ash added concrete beam under static loading.

Flexure and crack failures are very important for the future of concrete structures. Thus, in this section, the effect of 75% bottom ash ratio on the crack and flexural behaviour of reinforced concrete beams are assessed in detail.

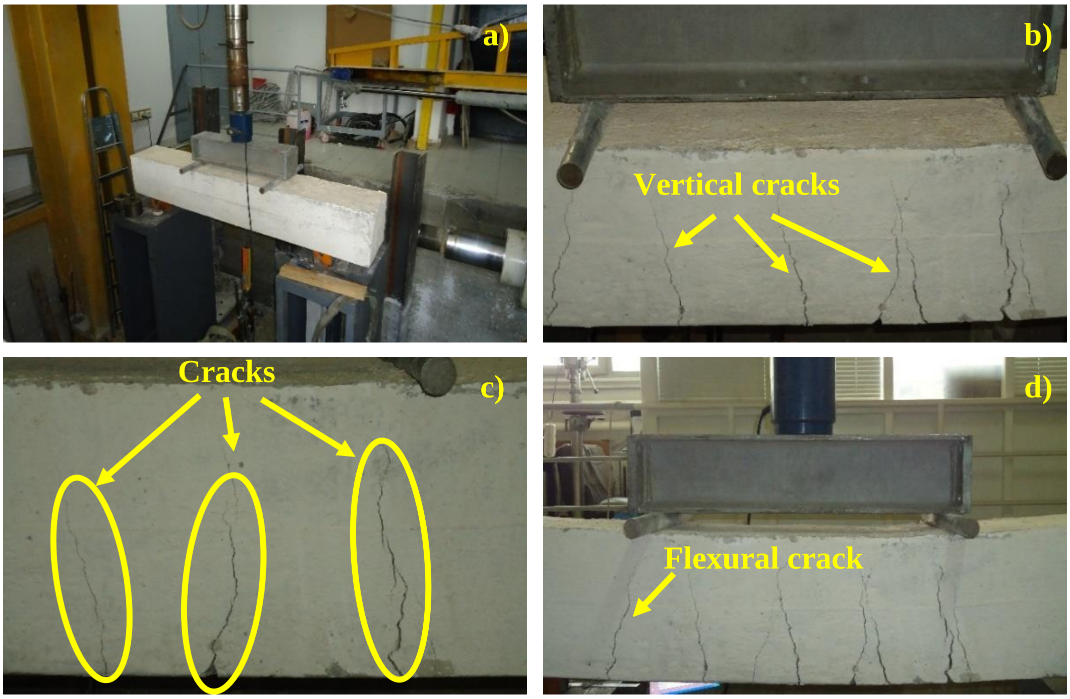

Fig. 5 Crack and flexure behaviour of concrete beam with 75% bottom ash.

Experimental results for 75% bottom ash ratio are shown in Fig. 5 and Fig. 6. According to Fig. 5, significant cracks (vertical and shear) are observed in the concrete beam. Very critical vertical cracks are obtained at middle of the beam as seen from Fig. 5b. Maximum crack width is 4.03 cm and it occurred at place where load is subjected. Moreover, significant flexural cracks are observed at bottom of the beam. These cracks are seen from Fig. 5d.

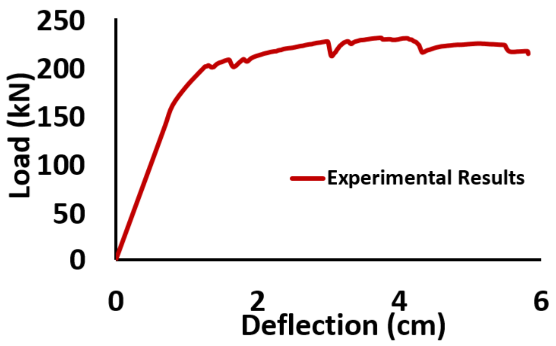

Fig. 6 Crack and flexure behaviour of concrete beam with 75% bottom ash.

When reference concrete beam compared with concrete beam with 75% bottom ash, more cracks are observed for 75% bottom ash ratio. This result proved the effect of bottom ash ratio on the crack behaviour of the concrete beams. In Fig. 6, load-deflection graphic of concrete beam under vertical load is shown in detail. Deflection line is linear and this linear line continues until 210.1 kN load. After 210.1 kN load, direction of deflection line changes and it is nonlinear line. Deflection line increases as linear line between 210.1 kN and 231.4 kN load. However, although vertical load increases after 231.4 kN, deflection value slightly diminishes. Maximum load carrying capacity of concrete beam is 238.0 kN. In addition, after the concrete beam is crushed and out of service, the maximum deflection in the beam is as 5.86 cm. This result is demonstrated very important information. It is clearly seen that when bottom ash ratio in the concrete is increased, maximum deflection rises depending on vertical load.

Three Dimensional Finite Element Model of Reinforced Concrete Beams

Three dimensional (3D) finite element modelling is an attractive method to monitor cracks and flexures in the reinforced concrete beams (RCBs). Thus, in this paper, experimental tests are confirmed by 3D finite element analyses and 3D model of reinforced concrete beam is performed according to planned dimensions of beam. While creating 3D models of RCBs, geometries and boundary conditions of original beam specimens created in the laboratory are taken into account for 3D model. 3D finite element models (FEMs) of RCBs are modelled using ANSYS software based on the finite element method.

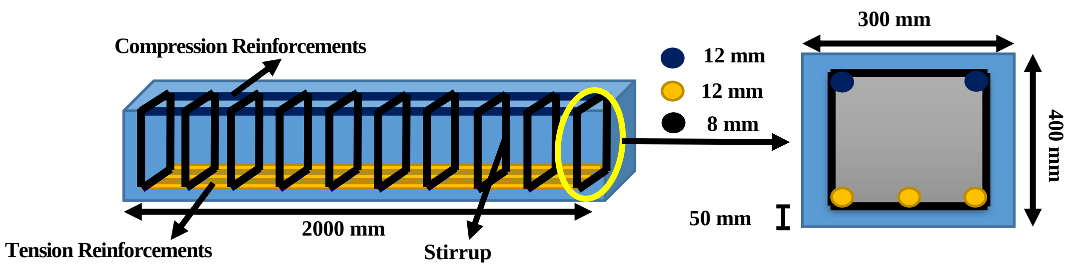

Fig. 7 Stirrups, compression and tension reinforcements in the RCB.

For 5 various 3D FEMs, all compression reinforcements, tension reinforcements and stirrups are modelled considering original geometries of RCBs. Total 2 reinforcements are used for compression reinforcements at top section of the beam and 3 reinforcements are considered for tension reinforcements at bottom of the beam. 12 mm diameter reinforcements are used for compression and tension reinforcements. Moreover, 8 mm diameter reinforcements are taken into account for stirrups. In the numerical analyses, special element types and material models for concrete and reinforcement are used. SOLİD65 nonlinear element type is considered for concrete, and LINK80 element type is used for compression and tension reinforcements. This element types are not randomly considered in this study. In the ANSYS software, these special element types are created for concrete and reinforces and these element types are taken into account for concrete and reinforces. In addition, for concrete, nonlinear multilinear mises plasticity material model is used and nonlinear bilinear mises plasticity material model is used for compression and tension reinforcements. These material models are special models for concrete and reinforces in the ANSYS software. Planned reinforced concrete beam for 3D finite element model is shown in Fig. 7.

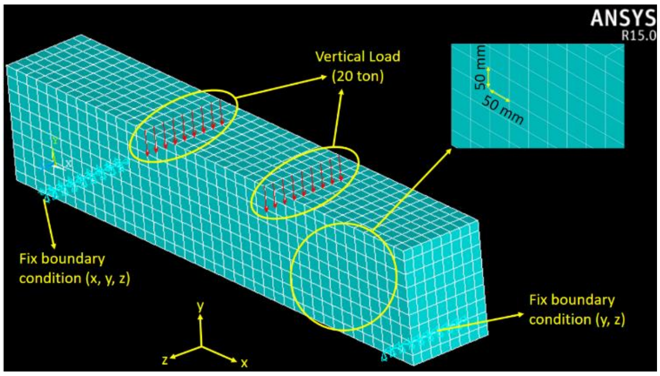

Fig. 8 View of vertical loads and boundary conditions in the 3D model of RCB.

Reinforced concrete beams are modelled considering 300x400x2000 mm dimensions. Details of 3D model of reinforced concrete beam is shown in Fig. 8. Firstly, element types of stirrups, compression and tensile reinforcements are defined to software and material properties obtained from experimental tests are described to the software using special codes. These material properties are elasticity modulus, shear modulus, Poisson’s ratio and density. Special real constants are defined to software for meshing of the 3D model. Movements of the boundaries of the 3D model must be restricted before 3D model is analyzed. Thus, the movement of the bottom of the foundation is freed in three directions (x, y, z) due to vertical load are subjected to middle of the beam. Moreover, one side of the 3D model is considered as pile and the movement of this side of the model is fixed in the x, y, z directions. Another side of the model is taken into account roller and it is restricted in the y and z directions. In the 3D finite element model, total number of the volumes is 165 and there are 3690 nodes in the 3D model. Moreover, there are 565 areas and 244 key points in the 3D model. While meshing the concrete beam, special mesh tools are used and firstly, lines are meshed. Then, stirrups, compression and tensile reinforcements are meshed in detail and finally, meshing of 3D volume is performed. The creating and meshing of the 3D model took a long time. Many problems are encountered during numerical analyses because three-dimensional finite element model of the beam has a great number of elements and nodes. In addition, during the analysis, convergence problems were encountered. For this reason, the finite element mesh is changed several times and a new mesh is created so that the correct result can be achieved and the program will not fail. It is clearly seen the suitable mesh range for this 3D model is as 50 mm.

Comparison of finite element analyses and experimental test results

When investigated deflection results in the beam for concrete beam with 25% bottom ash (Case 2), very close deflection results are observed between numerical and experimental test results. -4.01 cm deflection is obtained for experimental test and -4.02 cm deflection value is acquired at middle of the concrete beam for 3D numerical analyses. This verification gives us extensive information about the accuracy of the experiments. For Case 2, -5.86 cm deflection is acquired in the middle of the concrete beam for experimental test and -5.88 cm deflection is observed for the finite element analyses. This close numerical result shows verifying of experimental test results by 3D numerical analyses. Variation between experimental and 3D numerical results is 0%.34 for Case 4. In Fig. 9, load-deflection graphic is shown for Case 2 and very close deflection lines are observed for both test results. According to these results, it is obviously seen experimental test results are verified by 3D numerical analyses in this study. In addition, for experimental test results, it is clearly seen when bottom ash ratio in the concrete mixture is increased from 0% to 75%, deflection value in the beam under vertical load obviously rises. Same explanation is obtained for 3D numerical analyses of the 5 various concrete beams. Obtained cracks in the beam for experimental tests are very close to numerical analyses. In addition, the locations of the vertical and flexure cracks obtained from the experiments and numerical analysis are very similar.

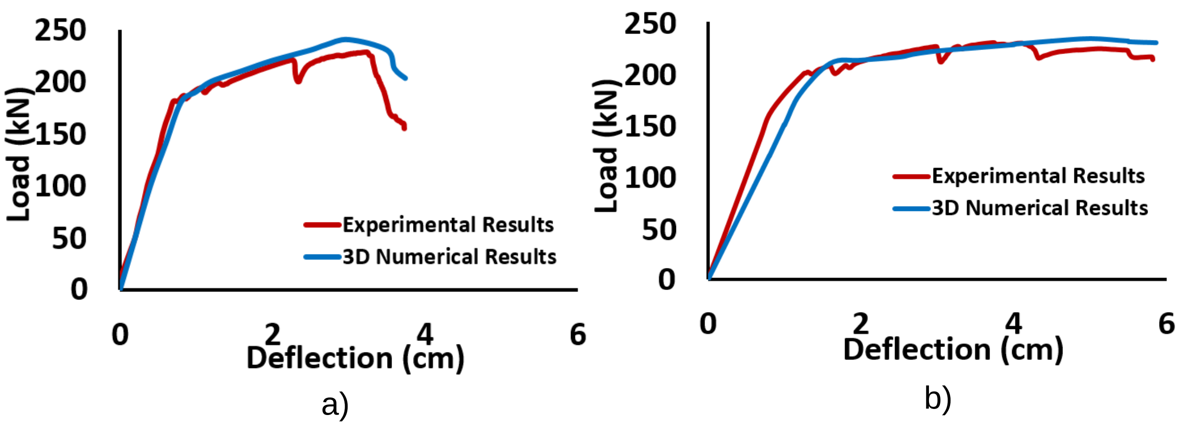

Fig. 9 Comparison of experimental deflection results and 3D numerical deflection results for; a) reference concrete beam, concrete beam with b) 75% bottom ash ratio.

Conclusions

Examination of flexural and crack behaviour of concrete structures under external loads is vital important for the safety of these structures. For this purpose, the deflection-load behaviour and crack behaviour of various concrete beams analyzed by experimental tests and 3D numerical modelling in this study. As a result, load depending deflection behaviors of these concrete beams are examined and evaluated in detail. 75% bottom ash fine aggregate ratio is used in the concrete mixtures. Material properties of these concrete beams obtained from experimental tests are used in the 3D finite element analyses. After concrete beams are prepared in the laboratory, these special concrete beams are subjected to crack tests using special device. Total 20-ton vertical load is practiced to the concrete beams with various bottom ash ratios and deflections in the beams are measured using LVDT device. Then, 3D numerical modelling of concrete beams is performed and 3D models of these beams are created considering original dimensions of them. Crack and flexural behaviors of the concrete beams are evaluated according to the experimental tests and 3D numerical analyses in detail. These important results are assessed as below:

- According to experimental test results, it can be clearly indicated that bottom ash ratio in the concrete mixture is enhanced, maximum deflection in the concrete beam increases. Maximum deflection in the middle of the beam is observed for concrete beam with 75% bottom ash ratio, and its numerical value is 5.86 cm. Moreover, 3.89 cm minimum deflection is obtained at middle of the beam for reference concrete beam.
- It is obviously seen that bottom ash ratio significantly affects crack behaviour of the concrete beams. Significant vertical and flexural cracks are observed in the beams depending bottom ash ratio. As bottom ash ratio in the concrete mixture is increased from 0% to 75%, cracks in the concrete beams obviously rises and widths of these cracks rise depending these bottom ash ratios.
- 3D numerical analyses are performed to confirm the experimental test results, and very close deflection and crack values are obtained between experimental and numerical results. In this study, load-deflection graphic for experimental test results are very similar to load-deflection graphic of 3D numerical analyses. Moreover, very close crack shapes are obtained for experimental and numerical tests. This clearly indicates that finite element simulation may be an excellent alternative for destructive laboratory tests with acceptable variations in the results. Thus, finite element simulation may effectively be used to predict the actual behavior of behaviour of the concrete beams.

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