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Experimental Validation of Reinforced Concrete Beam Incorporating Coal Fly Ash and Coal Bottom Ash Using Numerical Analysis

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Abstract: The environmental deterioration affected by the disposal of Coal Bottom Ash (CBA) from power stations has worsened as the energy demand has increased. In addition, the increased demand for concrete leads to an increase in aggregate consumption, which contributing to the depletion of natural resources. To prevent the immense amount of CBA waste and the destruction of natural resources, an initiative has been implemented to replace aggregate with CBA in concrete. The Reinforced Concrete (RC) beams underwent a four-point bending test. The test was done after 28 days of curing age. Therefore, this study was conducted to study the performance of RC beam incorporating CBA as fine and coarse aggregate replacement. The deflection, maximum load and cracking pattern of RC beam were determined. Beam with 100% coarse coal bottom ash 100% fine coal bottom ash resulted to the maximum load at 88 kN with maximum deflection at 18.87 mm. The RC beams were redesigned using the three-dimensional nonlinear simulation software ABAQUS in enable to identify and compare the simulation and experimental findings. The FEA result shows that ultimate load of FEA was within 5% range with the experimental results. The simulation results demonstrated that the proposed finite element model accurately predicted the RC beam's damage behaviour.

Keywords: Structure, coal bottom ash, abaqus software, concrete damage plasticity, finite element analysis

1. Introduction

Concrete is a solid, time-hardening building material made of cement, fine and coarse aggregates, and water. Concrete was the primary building material that was used in the majority of construction projects around the world [1]. The high demand for concrete can be related to the fact that in compared to other conventional construction materials, it has superior qualities in terms of its endurance, durability, ductility, and relative cost [2]. As the need for concrete increases, more raw materials such as sand and crush aggregate must be extracted from the environment [3]. The high demand for natural aggregates for constructing buildings leads to the depletion of natural resources. Therefore, it would be more useful both economically and ecologically if industrial wastes were used to partly or completely replace natural resources in concrete without affecting its properties [4].

On the other hand, sustainable concrete can be produced by substituting waste materials as a partial or total replacement in concrete. In Malaysia, the coal demand for power generation is expected to rise significantly by years due to the cheap cost and availability of resources compared with other resources [5]. Coal has become the main fuel source in Malaysian power plants to meet growing energy demand from 2005 to 2030 [6]. However, massive amounts of coal were burned in thermal power plants, resulting in large amounts of coal bottom ash [7]. In the current century,

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disposing of Coal Bottom Ash (CBA) has proven to be undesirable not only because of the rise in disposal costs, but also because of various health consequences [8]. A large amount of CBA created by coal combustion for power production is dangerous to human health and the environment [9]. CBA resembles natural river sand in appearance, and its particle size varies from fine sand to fine gravel [7]. Therefore, replacing CBA with alternative fine and coarse aggregates is a good initiative, as it may limit the depletion of natural resources and the production of coal ash waste.

Several researchers had studied the replacement of aggregate in cement, for example [10], reported that the replacement of CBA as sand replacement. 0%, 20%, 50%, 75% and 100% shows that compressive strength of experimental and control concrete samples increased significantly but remained comparable after 91 and 180 days. Furthermore, Kim & Lee [11] also study on the high replacement of CBA in concrete. Several experiments were conducted on 25%, 50%, 75% and 100% of CBA replacement in concrete. The results show that both fine and coarse aggregate had a greater impact on flexural strength than compressive strength. However, even though a few researchers have investigated the use of CBA as a fine and coarse aggregate replacement, there is currently lack of research on the use of CBA as a fine and coarse aggregate replacement in structural beams. In this study, ABAQUS explicit software was used to simulate a finite element model of reinforced concrete (RC) using CBA as a fine and coarse aggregate replacement to investigate the behavior and performance of RC beam. The experimental findings were compared with the FEA results for load-deflection and cracking pattern.

2. Methodology

2.1 Material Preparation

This research utilises cement, Coal Fly Ash, CBA, crush aggregate, sand, and water as its ingredients. 20% fly ash was added to the Portland cement Type 1 based on MS EN 197-1 [12]. CBA is collected from Johor, Malaysia's Tanjung Bin Power Plant. CBA was extracted and kept in a dry location to preserve its quality. In the laboratory, to reduce the size of CBA, a jaw crusher machine was used. After that, the CBA were sieved to 10 mm to 20 mm in size. The CBA retained in sizes ranging from 10 mm to 20 mm was used as coarse aggregate. Then, the passing through CBA was sieved again with a size of 4.75 mm. The same size was used for natural fine and coarse aggregate. Fig. 1 shows the fine and coarse of CBA respectively.

(a) (b)

Fig. 1 - (a) Fine Coal Bottom Ash (FCBA); (b) Coarse Coal Bottom Ash (CCBA)

2.2 Beam Preparation

It is important to learn structural analysis theory, which illustrates how a reinforced concrete structural component would perform under various loading conditions. The moment was designed using a stress block in accordance with the BS EN 1992-1-2:2004 code of specification [13]. 1500 mm x 200 mm x 150 mm beam was constructed. 100 mm spacing between 4Y12 high tensile bar and R6 mild steel round bar stirrups were installed. In this investigation, two different diameters were chosen for the primary reinforcement and shear link. Four 12 mm reinforcement bars were shortened to 1430 mm. The lateral reinforcement steel in the form of shear links was provided for these bars by supplying 6 mm diameter bars separated by 100 mm, and 80 x 130 mm shear link was bent to connect the primary reinforcement. Fig. 2 shows the experimental beam detailing.

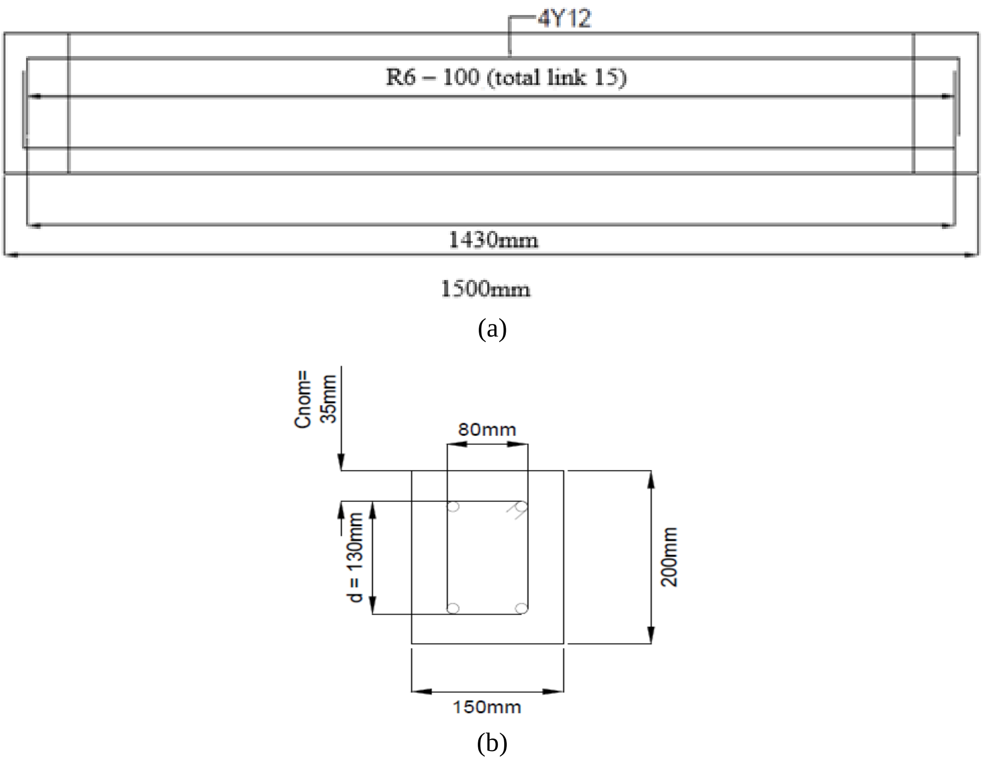


Fig. 2 - (a) Beam detailing; (b) beam cross section

2.3 Beam Casting

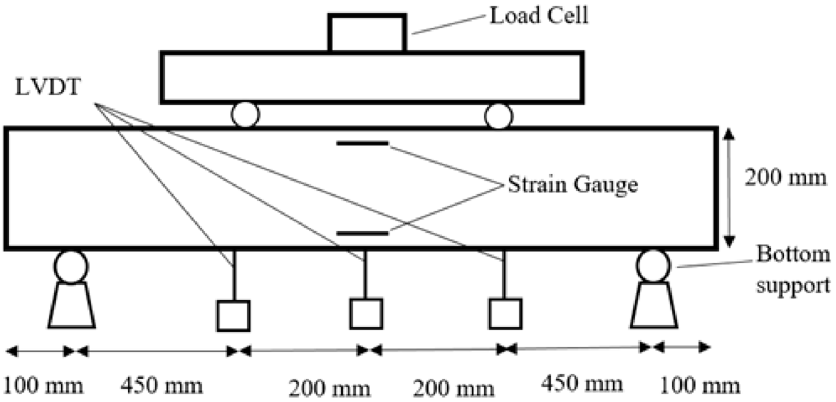
In this experiment, three proportions were produced. Three concrete compositions including coal bottom ash were cast and a control mixture. CBA was utilised as a volume replacement for coarse aggregate (crushed aggregate) and fine aggregate (sand). The percentages of replacement for coarse and fine aggregates were 50% and 100%, respectively. Table 1 represents the design of the concrete mix. After the cutting process, the main rebar and shear link were tied together based on the calculation. As seen in Fig. 3, the connected rebar was placed in the mould with 35 mm concrete cover. The concrete was poured into the mould, which was removed 24 hours later. After 28 days of curing, nine beam specimens were tested to determine the beam's flexural behaviour in terms of failure mode and cracking pattern. To determine the ultimate failure load, the beams were tested in line with BS EN 12390-5:2009 [14] requirements. Fig. 4 shows the four-point load test setup. Control RC beam, 100% coarse coal bottom ash 100% fine coal bottom ash and 50% coarse coal bottom ash 50% fine coal bottom ash are designated as Beam A, Beam B and Beam C, respectively.

Table 1 - Concrete mix design

Materials		Mix		
		Beam A	**Beam B**	**Beam C**
Cement (kg/m^3)		375	300	300
20 % of fly ash		0	75	75
Coarse aggregate	Crush aggregate (kg/m^3)	1035	0	518
	% of CCBA	0	100	50
Fine aggregate	Sand (kg/m^3)	780	0	390
	% of FCBA	0	100	50
Water		220	220	220

Fig. 3 - Tied rebar in mould with 35mm concrete cover

(a)



(b)

Fig. 4 - (a) Experimental four-point load test set up; (b) four-point load test set up

2.4 Finite Element Method

The finite element technique is considered as a trustworthy computer algorithm for investigating actual engineering problems involving complicated geometries, limitations, and loading conditions [15]. It is not only a reliable structural analysis tool, but it also saves time and resources. ABAQUS is a commercial finite element software that is used for modelling real-world applications due to its capability to produce and effectively analyse complex models. It represents linear and nonlinear mechanical behaviour of concretes, composite materials, and complex geometries [16], [17]. According to [18], who utilised ABAQUS to simulate fibre RC beams using the concrete damage plasticity (CDP) model, the predicted load defection curves were similar to the experimental beam values. The linear rule was well predicted the deflection curves in the post–yielding phase while significantly ignoring initial stiffness. Besides, using the ABAQUS/CAE software and the CDP failure analysis method, carried out three-dimensional non-linear modelling of a reinforced foamed concrete beam that included 20% palm oil fuel ash as well as 5% and 10% eggshell powder as partial cement replacement [2]. According to simulation results, the suggested finite element modelling accurately predicted the damage behaviour of foamed concrete. Therefore, by using finite element analysis, it helps to obtain the optimum analysis, solve the dynamic and specific problems of industrial engineering.

2.4.1 Description of Finite Element Analysis Model

A beam model was developed by concrete with eight nodes solid element (C38DR) meanwhile the geometry of the material used for reinforcing bars was modelled as a three-dimensional, two-node truss (T3D2). To simulate the bonding between the concrete and the reinforcement, the embedded method was used, assuming that the two elements were perfectly bonded. The CDP data includes compressive crushing and tensile cracking as failure modes. Flow rule, yield surface functions, and softening/hardening laws were used to describe the plastic behaviour of concrete. This behaviour can be simulated in the CDP model using the parameters including includes dilation angle (φ), plastic potential eccentricity (e), initial biaxial/uniaxial ratio (fbo/fco), the shape of the loading surface (Kc) and viscosity parameter. The materials properties were listed in Table 2.

Table 2 - Material properties parameter

Dilation angle	e	fbo/fco	K	Viscosity
40	0.1	1.16	0.6667	0

2.5 Finite Element Model

A few finite element analysis procedures were performed in the modelling approach for RC beams. First, using ABAQUS components, the geometry of each part including the solid rectangle, load, support, steel bars, and stirrups, was created. Then, all the elements were combined precisely into the position using the assembled task. Fig. 5 shows the detail of beam assembled. Next, for the interaction part, three interactions were used in this study, surface-to-surface contact, MPC Constraint with tie type and embedded region. After that, the loads were assigned boundary condition as pinned to restrain it from displacement of vertical and horizontal movement however the rotation was allowed. Lastly, before the analyse start, 10 mm mesh size were assigned to each element.

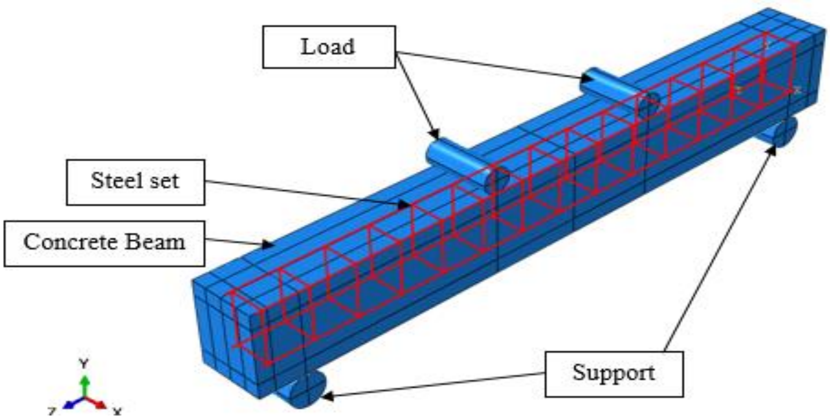


Fig. 5 - The details of beam assembled

3. Results and Discussions

3.1 Flexural Performance

According to BS EN 12390-5:2009 [14], the ultimate flexural strength of beam specimens was tested using a four-point test. The reinforced concrete beams undergo testing in a frame with a 100 kN load capability. The results for load – deflection is shown in Table 3. Beam A reacts almost linearly to the applied load and beam deflection up to the maximum load of 81 kN, with an optimum deflection of 18.1 mm. Meanwhile, RC beam containing high volume of CBA replacement shows a better result compared to Beam A. Beam B responds linearly between load and deflection until it achieves its maximum load of 88 kN and optimum deflection of 18.87 mm, while Beam C reached its maximum load with a high deflection value. The results presented that Beam C reached their maximum load at 78 kN with maximum deflection at 18.62 mm. This indicates that the replacement beams with 50 % coarse coal bottom ash and 50 % fine coal bottom ash were unable to support the load and caused a high value of deflection. The same pattern also found by [19]. The authors observed that RC beams constructed with recycled concrete coarse aggregate failed due to longitudinal steel yielding and concrete crushing in the compression zone. In accordance with the load–deflection relationship of beams at the mid span, more beam strength capacity may reduce the deflection [20].

Table 3 - Load-deflection data

Beams	Max deflection (mm)	Ultimate Load (kN)
A	18.11	81
B	18.87	88
C	18.62	78

3.2 Beam Cracking Pattern

Cracking pattern of the beam is the most important parameter that needs to be examined and measured throughout the experimental activity. Flexural fractures and shear cracks are two different forms of cracks that may develop. Based on the results of this experimental testing, it was observed that the initial flexural fractures in a beam typically appeared near the center of the beam and spread diagonally toward the point of failure. The maximum moment was near the bottom of the mid-section of the beam, where the flexure fractures appeared. The deflection rapidly increased as the strain in the steel bars reached the yielding point and leading to the expansion of the flexural cracks. Then, when the stress gets higher, larger cracks occur and move vertically upward into the compression zone, followed by the new crack between the primary ones. At the end, all the beams failed in flexure due to the yielding of the steel, following the break and crushing of the concrete in the compression zone. All the results show similar patterns of cracking with different ultimate loads. Fig. 6 shows the comparison cracking pattern of experimental beam and finite element analysis (FEA). Based on the results, the cracking pattern of FEA was in good agreement with the experimental results.

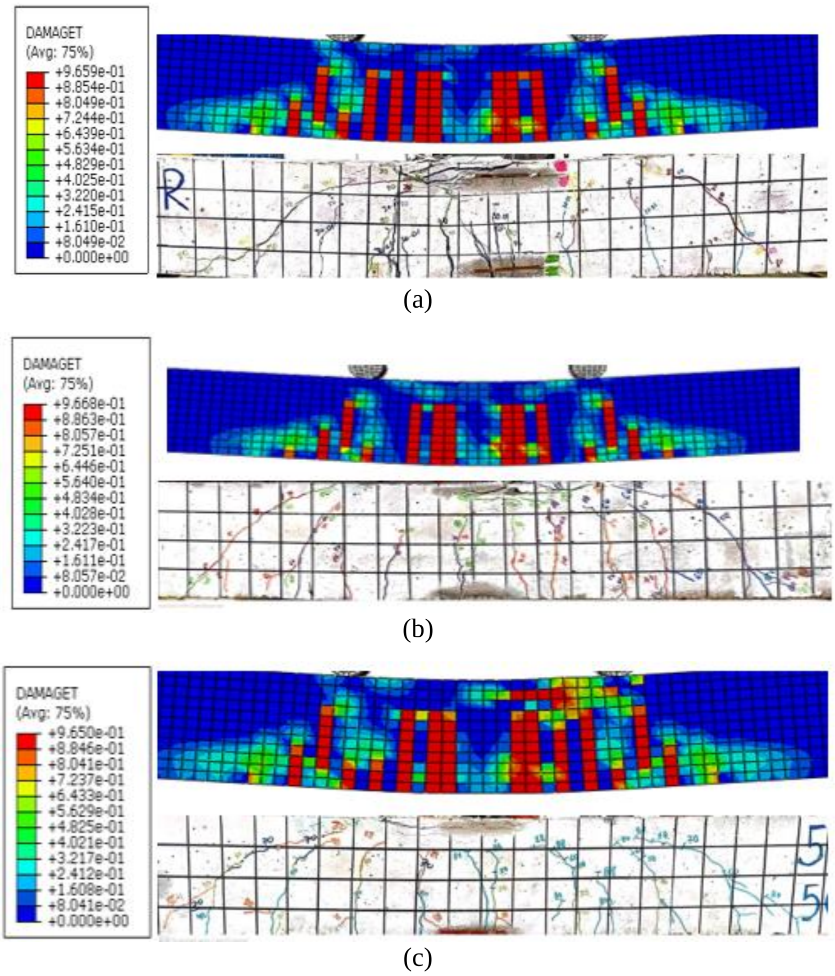
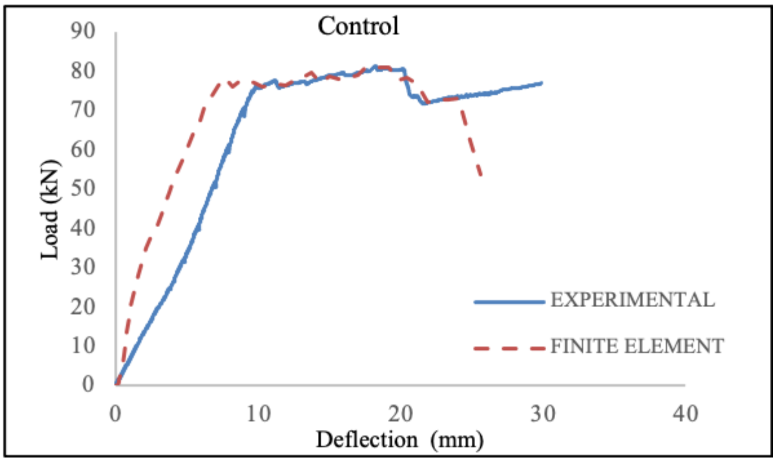


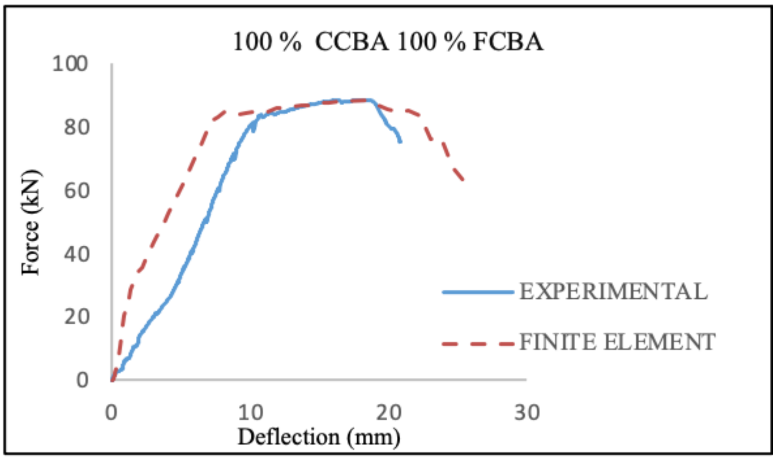
Fig. 6 - (a) Control beam racking pattern; (b) 100% CCBA 100% FCBA cracking pattern; (c) 50% CCBA 50% FCBA cracking pattern

3.3 Deflection Performance of FEA

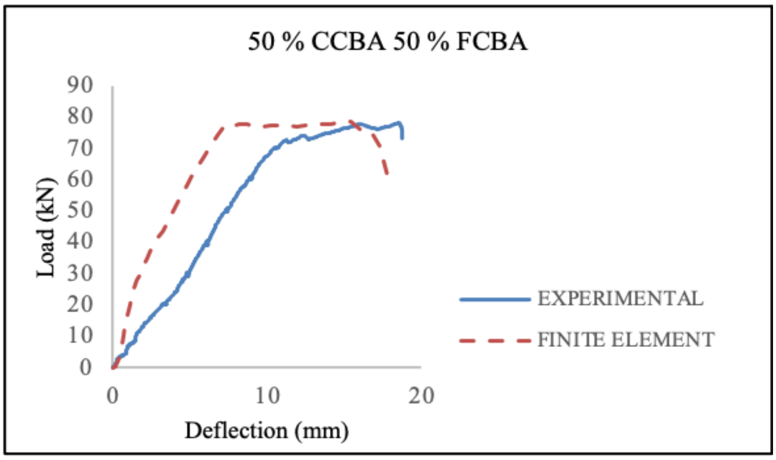
Based on the load vs. deflection graph shown in the Fig. 7 in terms of maximum load capacity, FEA and experimental data for all three specimens are in good agreement. The highest deflection of beam in FEA are shown in Fig. 8.



(a)



(b)



(c)

Fig. 7 - (a) Control concrete beam load vs deflection curve; (b) 100% CCBA 100% FCBA load vs deflection curve; (c) 50% CCBA 50% FCBA load vs deflection curve

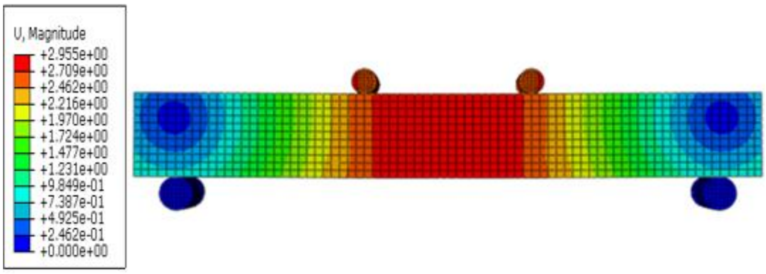


Fig. 8 - Deflection of RC beams using FEA

Based on the graph presented, the ultimate load of Beam A, Beam B and Beam C show in 5% range of difference between FEA and experimental. Beam B presented highest ultimate load at 86 kN with maximum deflection at 17.07 mm compared to the Beam A that indicate the ultimate load at 81 kN with maximum deflection at 17.56 mm. Meanwhile, Beam C shows the highest deflection at 15.80 mm at ultimate load 85 kN. This is due to the Beam C was unable to sustain load and cause high deflection. However, based on the load – deflection curve, the FEA shows stiffer results compare to the experimental results. There are numerous potentials contribute to the increasing stiffness of finite element models. The most significant finding is the existence of microcracks in the experimental beams' concrete, which may have resulted from drying shrinkage in the concrete or incorrect handling of the beams [21]. Besides, studies by [22] also resulted in similar patterns. The FEA resulted stiffer compared to the experimental results. This is due to the RC beam’s perfect bond assigned between steel and concrete. Overall, FEA findings slightly overestimated the strength, however, the analytical results were comparable to the experimental results.

4. Conclusions

By performing a four-point bending load analysis using the finite element technique, the flexural performance of RC beams using high volume bottom ash as a substitute for fine and coarse aggregate has been investigated in this study. The important results from this research are outlined as follows.

- RC beams incorporating with high volume of CBA resulted in better results compared to the control concrete. The result shows that beam incorporated with 100% CCBA 100% FCBA indicated the ultimate load at 88 kN and maximum deflection at 18.87 mm meanwhile control concrete RC beam has ultimate at 81 kN with maximum deflection at 18.11 mm.
- The ultimate load and maximum deflection of FEA were within 5% range with the experimental results even though the stiffness of FEA was stiffer compared with the experimental. Consequently, it can be stated that the simulation accurately predicted the RC beam utilizing CBA.
- The cracking pattern that developed in FEA is similar with the experimental results.

Acknowledgement

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