Flexural Behaviour of a Reinforced Concrete Beam Blended with Fly ash as Supplementary Material

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Abstract. Two small-scale reinforced concrete beams, one made of ordinary Portland cement (NC) and the other blended with supplementary material using fly ash (SMFA), were investigated to gain insights into their flexural behaviour. Class F fly ash by 15 per cent of the mass of cement was added in the concrete mix of SMFA beam, enabling the reduction of cement usage. The specimens were designed under-reinforced having low steel bar ratio and were tested under four-point bending to failure. To ensure the beam failing in flexure, the M/Vd ratio of 3.2 was customary to allow the development of flexural cracks transpired over the centre span as the load further increased. Predictions incorporating manual calculation and computer simulation using Response-2000 were also performed and compared against the experimental data. The results showed that the NC and SMFA beams were generally equivalent in terms of load-deflection response, crack pattern, and mode of failure. Nonetheless, it should be marked that the load-carrying capacity of the SMFA beam was 22 per cent higher than that of NC beam, while the deflection of the SMFA beam was found to be significantly higher. Predictions from the manual calculation and computer simulation using Response-2000 were also in good agreement with the results obtained from the experiment.

Keywords: reinforced concrete beam, flexural behaviour, fly ash, cracks, response-2000

1. Introduction

Fly ash, otherwise known as pulverised fuel ash in the United Kingdom, is one of the coal combustion products which is often classified as waste material. Its origin derives from the use of coal-fired electric and steam generating plants. The massive operation of electrical power plant worldwide making use of coal has triggered numerous amounts of fly ash which is increasing every year. In 2014, the utilisation of coal in the global power plant industry was about more than 550 megatons, prompting the massive existence of by-product materials which consisted of 70 per cent fly ash, 25 per cent bottom ash, and 5 per cent boiler slag [1-2]. However, only less than 20 per cent of the sums have been utilised in the construction sectors [3].

Differing to one another, fly ash comprises mainly of extremely fine, glassy spheres which are identical with cement whereas bottom ash resembles the appearance of sand texture. Their roles as cement replacement have gained approval among researchers worldwide, and studies have been carried out over many decades to provide a better understanding of their nature. It is also of importance to highlight that the use of this by-product material is generally aimed to substitute some of the cement contents with a certain percentage in addition to creating eco-green structures. The
usage of fly ash, for instance, is well known in concrete manufacturing industry where it is regularly adopted as supplementary cementitious or pozzolanic material.

In accordance with ASTM C618 [4] as to what is presented in Table 1, fly ash is characterised by three classes according to its chemical compounds. These classes are unique as they offer distinctive properties. Class N fly ash is known as raw and calcined natural pozzolans complying with diatomaceous earth, opaline cherts and shales, tuffs and volcanic ashes or pumicites, or various materials requiring calcination to induce satisfactory properties. Class F fly ash is known to have high silicate and low calcium content which tends to diminish the compression strength. Ca(OH)₂ in the pozzolanic reaction inherited in Class F fly ash also produces C-S-H that will certainly increase durability and decrease permeability even from sulphate and chloride attack [5]. Meanwhile, Class C fly ash is attributed by low silicate and high calcium content. In addition, some Class C fly ashes may comprise of lime contents higher than 10 per cent. This makes Class C fly ash more like a cementitious material which quickly hydrates and hardens, and it allows the increase of compression strength of concrete as well. Class F fly ash is regularly used as replacement approximately 15 to 25 per cent by mass of cement, whereas Class C is between 15 to 40 per cent [6-7].

Table 1. Chemical requirements of fly ash [4]

| Class | N   | F   | C   |
|-------|-----|-----|-----|
| Silicon dioxide (SiO₂) plus aluminium oxide (Al₂O₃) | 70.0 | 70.0 | 50.0 |
| plus iron oxide (Fe₂O₃), min, % | 4.0  | 5.0  | 5.0 |
| Sulfur trioxide (SO₃), max, % | 3.0  | 3.0  | 3.0 |
| Moisture content, max, % | 10.0 | 6.0  | 6.0 |
| Loss on ignition, max, % | *    |      |     |

Note: the use of Class F pozzolan containing up to 12.0% loss on ignition may be approved by the user, if either acceptable performance records or laboratory test results are made available.

To date, the central of the utilisation of fly ash has not only been focused on substituting the amount of cement used in normal concrete, but it has also been utilised mainly as one of the key constituents in cementitious composites such as engineered cementitious composite (ECC) which is also known as bendable or flexible concrete [8-11]. The motive is to provide the initiative alternative to replace the overriding cement usage thereby reducing anthropogenic activities causing emissions of carbon dioxide (CO₂) from cement fabrication [12]. Accordingly, it is a significant cause as the usage of a high volume of cement would result in undesired hydration heat as well as high material cost [13]. Furthermore, fly ash blended in concrete would make it more durable and more resistant from attack of alkaline sulphate and reactive reactors [14-15]. Fly ash has also been functioned to alleviate the development of a network of fine cracks on a surface such as due to creep and shrinkage, debonding, and other defects [16].

Referring to what has been addressed above, this current work is aimed to compare the behaviour of reinforced concrete beams with one made of normal concrete (NC) and the other made of concrete blended with fly ash (SMFA). To a great extent, the response, cracking patterns, and mode of failure are assessed and discussed herein to gain insights into their behaviour. Computer analysis using Response-2000 is also presented in this paper for comparative purposes. In the early stage of this study, the beam was designed to fail in flexure rather than in shear. This was to ensure that during loading, the member would exhibit visible signs of distress in the form of, for example, extensive cracking or large deflection [17][18] which, in contrast with shear failure that is associated with the brittle nature of concrete, would occur suddenly with little or even no warning [19]. To avoid shear governing the response when the beam was subjected to loads, it was of utmost importance to provide adequate shear reinforcements along the shear span. Furthermore, shear span-to-effective depth ratio was determined to exceed the minimum ratio as specified in the design specifications.
Table 2. Details of the beam cross-section

| Width b (mm) | Height h (mm) | Effective depth d (mm) | Length L (mm) | Span a (mm) | a/d |
|--------------|--------------|------------------------|---------------|------------|-----|
| 100          | 200          | 157                    | 2000          | 500        | 3.2 |

Table 3. Tensile properties of reinforcing bars

| Diameter (mm) | Area (mm²) | Yield strength fᵧ (MPa) | Ultimate strength fᵤ (MPa) | Elastic modulus Eₛ (GPa) | Strain hardening εsh (%) | Ultimate strain εᵤ (%) |
|---------------|------------|-------------------------|----------------------------|--------------------------|--------------------------|-------------------------|
| 8             | 50.3       | 397                     | 540                        | 200                      | 1.1                      | 15.8                    |
| 10            | 78.5       | 559                     | 649                        | 200                      | 1.4                      | 10.3                    |

Table 4. Summary of concrete mix

| Specimen | CEM I (kg/m³) | 10 mm (kg/m³) | Fine (<3mm) (kg/m³) | Class F Fly ash (kg/m³) | HRWR (g/m³) |
|----------|---------------|---------------|---------------------|-------------------------|-------------|
| Beam NC  | 525           | 1054          | 764                 | -                       | 5.5         |
| Beam SMFA| 470           | 1052          | 731                 | 80                      | 5.5         |

Note: 10mm is a graded crushed granite; HRWR is a high range water reducer

Table 5. Summary of 28-day compressive strength obtained from 300 mm cylinders

| Beam | Mean (MPa) | Standard of Deviation, SD (MPa) | Specific Gravity (kN/m³) |
|------|------------|---------------------------------|--------------------------|
| NC   | 47.2       | 2.3                             | 25.6                     |
| SMFA | 50.8       | 2.3                             | 25.8                     |

2. Experimental Methods

2.1 Test Specimens
A series of small-scale reinforced concrete beams with different matrix constituents were fabricated and tested in the Warehouse of PT. Wijaya Karya Beton Tbk. in Pasuruan, but only the results of two beams are presented in this paper. These two beams, hereafter referred to as Beam NC and Beam SMFA, had five longitudinal reinforcements: two as compression (top) and three as tension (bottom) bars. Rectangular closed transverse reinforcements spacing 10 cm at each, past the supports, were provided to increase the shear resistance, thereby ensuring the beam not failing in a brittle manner. Figure 1 shows the schematic of beam geometry and loading setup, with the dimensions and reinforcement details presented in Table 2 and Table 3.

2.2 Material Properties and Fabrication
The concrete mix proportions used to fabricate the beams are presented in Table 4. The concrete mix for both beams had a water-to-cement ratio of 0.3, coarse aggregate with a maximum aggregate size of 10 mm, fine aggregate (<3 mm), and CEM I 42.5 R-NA Portland cement to DIN 1164 [20], and a high range water reducer (TamCem 60). For each beam, mixing was done in a single batch using a 150-litre pan mixer.

Each of the beams was cast into a steel formwork with dimensions of 100×200×2000 mm³, along with nine standard 300 mm height cylinders designated for compression testing after 7, 14 and 28 days. A summary of concrete compressive strength obtained in accordance with ASTM C39/C39M–
14 [21] is presented in Table 5. The fresh concrete was poured into a mould followed by the use of internal vibration employing a poker to eliminate air bubbles which can substantially weaken the concrete structures. Upon this step, the concrete surface at the top of the beam was flattened to ensure the beam has similar cross-section throughout the length.

The beam was left for 24 hours to set and upon this, the mould was dismantled. The beam was transferred to a curing room until required for testing which is generally 28 days after casting. During the curing process, the specimens (beams and cylinders) were covered in frequent wetted-wipes and wrapped up using plastic to prevent excessive hydration from cement that might cause premature shrinkage cracks.

### 2.3 Chemical Compounds

Cementitious material signified as binders of the concrete specimens were characterised employing the application of X-ray Fluorescence (XRF) using Rigaku RIX-3000 model to obtain information on the chemical compounds (see Table 6 and Table 7 for Portland cement and Class F fly ash respectively). As presented in the tables, it is apparent that the mass of calcium silicates (CaO and SiO$_2$) found in Portland cement clinker was higher than two-thirds of the total mass of the sample, signifying its classification as ordinary Portland cement. On the other hand, the prominence of chemical contents found in fly ash is in good agreement with Class F classification as to what is presented in Table 1. In respect to other materials playing a role as aggregates, they were also analysed with consideration of their physical properties, specific gravity, volume weight, mud content, gradation, and fineness modulus. Details of the analysis are summarised in Table 8.

#### Table 6. Chemical properties of CEM I

| Compound | Content (%) |
|----------|-------------|
| CaO      | 62.87       |
| SiO$_2$  | 20.33       |
| Al$_2$O$_3$ | 3.1        |
| FeO      | 4.81        |
| MgO      | 0.1         |
| SO$_3$   | 2.5         |
| K$_2$O   | 0.45        |
| TiO$_2$  | 0.43        |
| V$_2$O$_3$ | 0.02      |
| CuO      | 0.075       |
| ZnO      | 0.027       |
| SrO      | 0.053       |
| ZrO$_2$  | 0.03        |
| BaO      | 0.06        |

#### Table 7. Chemical properties of Class F fly ash

| Compound | Content (%) |
|----------|-------------|
| CaO      | 9.32        |
| SiO$_2$  | 43          |
| Al$_2$O$_3$ | 12.8       |
| FeO      | 26.8        |
| MgO      | 0.17        |
| P$_2$O$_5$ | 0.81       |
| K$_2$O   | 2.36        |
| TiO$_2$  | 1.47        |
| V$_2$O$_3$ | 0.074      |
| Cr$_2$O$_3$ | 0.044    |
| CuO      | 0.05        |
| MoO$_3$  | 3           |
| BaO      | 0.25        |

#### Table 8. Physical properties of fine and coarse aggregate

|                     | Fine (< 5 mm) | Coarse |
|---------------------|---------------|--------|
| Specific gravity    | 2.68          | 2.70   |
| Weight volume       | 1.39          | 1.41   |
| Mud content         | 2.44          | 3.37   |
| Fineness modulus    | 6.78          | 2.77   |

#### 2.4 Test Setup

The photo test arrangement used to test the beams is shown in Figure 2. All beams were simply supported and were tested under four-point bending, with the span between the supports being 1700 mm and the distance between point loads measured from midspan being 700 mm thereby giving a
shear span-to-effective depth ratio of 3.2. The load was applied using an automated-operated hydraulic jack placed on the centre of a stiff spreader beam to distribute the load to two 25 mm steel bars. The pressure was applied in 50 psi (344.5 kN/m²) increments until failure with a piston area of 0.02 m² thereby giving the equal incremental load of 6.89 kN.

Cracks at each load increment were marked, and photos were also taken to document the crack pattern. The load was measured using 1000 kN Tokyo Sokki load cell mounted to the head of the jack. On top of that, longitudinal strain and beam deflection were also recorded using the strain gauge FLA 5-11 and linear variable displacement transducer (LVDT) respectively. The strain gauge was attached to the tension (bottom) bar, and the LVDT was positioned beneath the beam at midspan. Prior to set up, the surface of the beam was painted white, and 5-mm square gridlines were prepared to ease the identification of the location of cracks throughout the course of loading. A static digital camera was also prepared and placed in front of the beam surface for crack mapping purposes using the digital image correlation (DIC) technique [17,19]. However, the DIC results are not presented herein.

**Figure 1.** Schematic drawing of beam geometry and loading setup
Figure 2. Test setup and instrumentations

Figure 3. Observed and predicted load-deflection responses of all beams

Observed final crack patterns at failure
3. Results and Discussion

3.1 Load-Deflection and Crack Pattern

A comparison of the observed load-deflection curves of the Beam NC and Beam SMFA is presented in Figure 3, along with the prediction from Response-2000 overlaid in the curves and crack patterns shown in Figure 4. With respect to the experimental results, it is apparent that the initial responses from the curves are linear elastic, portraying significant increase in load with a marginal increase in beam deflection.
During the increase of load, the sign of cracks developed for the first time on the tension face of the beam over the centre span. The first initiation of visible cracks occurred in the Beam NC corresponds to the load of ~13.7 kN, whereas in the Beam SMFA the initial cracks occur at the load of ~20.7 kN. The hand calculation of predicted load at cracked section \( P_{cr} \) is also in good agreement with the trend. In general, the load upon this initial cracking is still proportional to the deflection whereby there is somewhat a degradation of stiffness. As the load is further increased, a more significant stiffness reduction is apparent, and the response is thus in the nonlinear region. It is also noticeable that a transitional region from both beams which is attributed by the yield of tension bars is found to be slightly varied. Apart from the response, however, the progression of cracks is significant, and there are some inclined cracks propagating toward the loading plate as the load went up (see Figure 4(a) and 4(b)).

The Beam NC is proven to exhibit lower load capacity compared to the Beam SMFA. This lower-than-observed load capacity is a result of lower compressive strength as well as the yield strength of steel inherited in the NC specimen. Apart from that, it is yet evident that the NC specimen demonstrates better ductility, showing extensive ductile plateau. The Beam NC and Beam SMFA eventually fail in flexure at a load of 87 kN and 93 kN, respectively due to sudden concrete crushing at the top next to point loads (refer to Figure 4(a) and 4(b)). However, the failure is regarded flexure demonstrating extensive crack developments upward the neutral axis accompanied by large beam deflection.

With reference to the prediction from computer simulation, it is noticeable that the results from Response-2000 tend to slightly underestimate the load capacity and the deflection. The discrepancy is marginal, in particular to the prediction of maximum load-carrying capacity. It is interesting to note when designing the beam under-reinforced section, the contribution of yield and ultimate strength of steel determine the changes in load and deflection level which may cause the difference. The significance is, however, proven as the response is similar to one another. Another thing worth noting is, the crack pattern predicted by the software is identical with the observed crack during testing.

3.2 Manual Calculation
The manual calculation is also performed to provide another comparison with regard to the ultimate load level that represents the flexural capacity of a member. It is based upon basic concrete mechanics that adopt the force equilibrium state. As such, the forces in compression (C) fibre of the beam cross-section should be similar to the forces in tension (T) fibre (see Figure 5). The formulations used to calculate the capacity are expressed in Equation 1 through Equation 5.

![Figure 5. Doubly reinforced concrete stress-strain diagram: (a) cross-section; (b) strain diagram; and (c) stress diagram](image-url)
Using the above equations, it is found that the maximum load capacity \( P_{\text{ult}} \) of 75 kN calculated from the nominal moment is nearly similar to that found using Response-2000 (see the red line in Figure 3). The discrepancy is marginal as the maximum load capacity predicted in Response-2000 is about 81 kN. Overall, all predicted response tends to underestimate the response, albeit the trend is identical towards one another.

### 4. Conclusions

A series of experimental investigations into the flexural behaviour of reinforced concrete beams is presented. Emphasis has been made on the utilisation of supplementary fly ash material blended with Portland cement clinker and other aggregates with regard to its structural response, crack patterns and mode of failure. The results of computer simulation adopting the modified compression field theory (MCFT) and manual calculation have also been included in this study for comparative purposes. Based on the experimental and analytical work presented, the following conclusions are drawn.

1. This work demonstrates that the utilisation of supplementary material such as fly ash is promising as principal means to diminish the anthropogenic activities’ impact due to cement fabrication.
2. In general, the results show that the Beam SMFA has a similar response to the Beam NC despite the reduction of cement content.
3. It is shown that the load-carrying capacity of Beam SMFA is slightly higher than Beam NC with the increase in the proportion of 6.37 per cent.
4. It is apparent that all test specimens relatively shows extensive vertical and inclined cracking patterns and ductility, suggesting the design is tension-controlled and the failure mode is in flexure.
5. The prediction from computer simulation using Response-2000 is in good agreement to those obtained in the manual calculation and as per observed beam specimens.

### References

[1] Fisang LJ, Djuric M, RM Neducin, J Ranogajec, and A Mihajlov 1995 An optimization of fly ash quantity in cement blending *Cem. Concr. Res.* 25 71489–90

[2] Ammasi A K and Ragul 2018 Strength and durability of high volume fly ash in engineered cementitious composites *Mater. Today Proc.* 5 24050–8

[3] Ebnesajjad S 2011 Environmental Impacts of Coal Mining & Utilization. A Complete Revision of Environmental Implications of Expanded Coal Utilization *Handbook of Adhesive and Surface Preparation Technology* (Oxford: William Andrew-Elsevier) 445

[4] ASTM C618-05 *Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete* 2005

[5] Mccarter W J, Chrip T M, Starrs G, Adamson A, Basheer P A M, Nanukuttan S V, Srinivasan
S 2013 Characterization of physio-chemical processes and hydration kinetics in concretes containing supplementary cementitious materials using electrical property measurements *Cem. Concr. Res.* *50* pp 26–33

[6] Mehta P K and Gjørv O E 1982 Properties of portland cement concrete containing fly ash and condensed silica-fume *Cem. Concr. Res.* *12* 587–95

[7] Şahmaran M, Özbay E, Yücel H E, Lachemi M and Li V C 2011 Effect of fly ash and PVA fiber on microstructural damage and residual properties of engineered cementitious composites exposed to high temperatures *J. Mater. Civ. Eng.* *23* 1735–45

[8] Singh M, Saini B and Chalak H D 2019 Performance and composition analysis of engineered cementitious composite (ECC) – A review *J. Build. Eng.* *26* JBE(2019)100851

[9] Taylor P C and Tait R B 1999 Effects of fly ash on fatigue and fracture properties of hardened cement mortar *Cem. Concr. Compos.* *21* 223–32

[10] Gao S, Zhao X, Qiao J, Guo Y and Hu G 2019 Study on the bonding properties of Engineered Cementitious Composites (ECC) and existing concrete exposed to high temperature *Constr. Build. Mater.* *196* 330–44

[11] Li V C 2003 On engineered cementitious composites (ECC) a review of the Material and Its Applications *J. Adv. Conc. Tech.* *1* 3 215–30

[12] Şahmaran M, Lachemi M and Li V C 2010 Assessing mechanical properties and microstructure of fire-damaged engineered cementitious composites *ACI Mater. J.* *107* pp 297–304

[13] Zhang J, Liu G, Chen B, Song D, Qi J and Liu X 2014 Analysis of CO$_2$ emission for the cement manufacturing with alternative raw materials: A LCA-based framework *Proc. Int. Conf. on Applied Energy (Taipei)* (Taiwan: Elsevier) *61* 2541–45

[14] Bahedh M A and Jaafar M S 2018 Ultra high-performance concrete utilizing fly ash as cement replacement under autoclaving technique *Case Stud. Constr. Mater.* *9* C SCM(2018)e00202

[15] Komara I, Tambusay A, Sutrisno W and Suprobo P 2019 Engineered cementitious composite as an innovative durable material: a review *ARPN J. Eng. Appl. Sci.* *14* 4 822–33

[16] Yang E H, Yang Y and Li V C 2007 Use of high volumes of fly ash to improve ECC mechanical properties and material greenness *ACI Mater. J.* *104* 620–8

[17] Suryanto B, Morgan R and Han A L 2016 Predicting the Response of Shear-critical Reinforced Concrete Beams using Response-2000 and SNI 2847:2013 *Civ. Eng. Dimens.* *18* 1 pp 16–24

[18] Suryanto B, Tambusay A and Suprobo P 2017 Crack mapping on shear-critical reinforced concrete beams using an open source digital image correlation software *Civ. Eng. Dimens.* *19* 2 93–8

[19] Tambusay A, Suryanto B and Suprobo P 2018 Visualization of shear cracks in a reinforced concrete beam using the digital image correlation *Intr. J. Adv. Sci. Eng. Inf. Tech.* *8* 2 573–8

[20] DIN EN 197-1 *Special cement composition and conformity evaluation 2000*

[21] ASTM C39-C39M-14 *Standard test method for compressive strength of cylindrical concrete specimens 2014*

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