Flexural behaviour of the functionally graded concrete beams using two-layers and three-layers configuration

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Abstract. Studies related to the bending behaviour of functionally graded concrete (FGC) beams are still investigated to explore the possibility of the more cost-efficient casting techniques and to produce high-performance FGC beam elements simultaneously. Previous research shows that the manufacture of FGC beams by combining two concrete mixes in two layers can increase the stiffness of the elements but it reduces the beam ductility. Research concentrating on the FGC beams with additional numbers of concrete layers was analysed in this study. Four pieces of FGC beams measuring 120 x 240 x 2200 mm were prepared with concrete strength of 25 MPa (NA); 30 MPa (NB); 30-20 MPa (GBA); and 30-20-30 MPa (GBAB). The specimens were tested in the laboratory using a four-point bending method. The experimental data consisting of the load increments and the mid-span deflections are further analysed to compare the resulting (1) maximum load-carrying capacity; (2) maximum deflection; (3) beam stiffness; (4) moment-curvature; and (5) ductility. The result shows that (1) the GBAB exhibited 0.83% greater maximum loads than the GBA; (2) the GBAB deflected 29.52% lesser than the GBA; (3) the GBAB possesses stiffness 12.03% greater than the GBA; (4) the GBAB exhibited higher resulting yield points and ultimate state than the GBA at the moment-curvature relationship; and (5) the GBAB was 20.06% less ductile than the GBA.

1. Introduction
Research related to functionally graded concrete (FGC) is still continuing as environmental issues require human-being to reduce the use of cement in construction and to reduce the contribution of carbon dioxide to the air [1-3]. FGC is one of the concrete innovations that is proven to reduce the use of cement while still maintaining the performance of the structures. Applying FGC in building structures could reduce 6.48 – 9.72 % of cement use. The FGC is created by combining 2 (two) or more concrete mixes that possess a distinct concrete strength into structural members [4]. This concrete technology optimises the use of concrete materials according to its characteristics. The FGC configures the higher concrete strength to concentrate on the extreme compression fibre and the lower concrete strength on the extreme tensile fibres. In structural analysis, the tensile strength of concrete is neglected as the presence of longitudinal rebar that will replace the concrete in withstanding the tensile stress [5-10].

Previous studies showed that FGC beam created from two layers of concrete mixes with different strength resulted in higher structural stiffness than the beam cast from lower concrete strength. The increase of beam stiffness is accompanied by the increase of resulting maximum loads and the decrease of midspan deflection [11-12]. Unfortunately, the increase of structural performance is somewhat not significant and requires further investigation of this research programme.
In this research, authors would like to investigate the possibility to increase the structural performance of the FGC beam by adding the number of concrete layers from two to three layers but still using two concrete mixes. The higher concrete strength is planned to be cast at both of the compression and the tensile fibre of beams to improve the bonding strength between the longitudinal rebar and the concrete; meanwhile the lower concrete strength is situated at the middle depth area of the beam as the lesser stress occurs around neutral axis so it does not require high reinforcement from concrete and rebars. In the end, the authors would like to compare the resulting data from 3 layers FGC beam with the 2 layers FGC beam in terms of (1) maximum load-carrying capacity; (2) maximum deflection; (3) beam stiffness; (4) moment-curvature; and (5) ductility

2. Research methodology

2.1. Specimens preparation

This research was conducted experimentally at the Laboratory of Material Testings and Structure, Universitas Negeri Malang, Indonesia. Two groups of specimens were prepared, which were controlling specimens and testing specimens. The controlling specimens consisted of conventional reinforced concrete (RC) beams for the bending test; meanwhile, the testing specimens only consisted of FGC beams created from two layers of concrete mixes and FGC beams from the layers of concrete mixes. Details of specimens used in this research are shown in Table 1.

| Specimen Group  | Notation | Description                              | Amount (pieces) |
|-----------------|----------|------------------------------------------|-----------------|
| Controlling     | NA       | Conventional RC beams 25 MPa             | 2               |
|                 | NB       | Conventional RC beams 30 MPa             | 2               |
| Testing         | GBA      | Reinforced FGC beams with 2 layer        | 2               |
|                 |          | configuration (30 – 25 MPa)              |                 |
|                 | GBAB     | Reinforced FGC beams with 3 layer        | 2               |
|                 |          | configuration (30 – 25 – 30 MPa)         |                 |

2.2. Reinforced concrete beam design

The beams for controlling specimens and the testing specimens were expected to undergo failure in flexure due to the design of a/d = 3.04. All of the RC beams were prepared to have 2200 mm in length and 120 mm x 240 mm for the cross-sectional dimension. The beams were doubly reinforced with 2D10 and 2D10 for the longitudinal rebars and were installed with d6-100 for stirrups in supports and d6-175 in midspan.

2.3. FGC casting configuration

Both GBA and GBAB specimens are made of two concrete mixes. those were 30 MPa and 25 MPa. The gradation pattern was created vertically. Further, for the GBA, the 30 MPa concrete mix was placed at the compression fibre while the 25 MPa mix was at the tensile fibre. The two concrete mix shares the depth of beams by half. Intensive compaction procedures were conducted using shaft vibrator to eliminate distinct transition of two different concrete mixes. For the GBAB, the concrete casting was initiated by placing the 30 MPa mix by one-third part of beam depth, continued by placing the 25 MPa mix on the previous layer by another one-third part of beam depth, and was finished by pouring the 30 MPa mix until full. The vibration was also applied to each stage of concrete casting to create a smooth transition of concrete strength. The illustration of concrete casting configuration for GBA and GBAB are displayed in Figure 1.
2.4. Four-point bending test
The 28 days old RC beams were set on the loading frame for conducting four-point bending test. To ease the observation of crack propagation during the test, the beams were all dyed white and grid using a marker. The author utilised hydraulic jack, load cell, loading head, data logger, and dial gauges during the test. The data consisting of midspan deflection and incremental loads were analysed from the reading of the dial gauges and the data logger. The test setup is illustrated in Figure 2.

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**Figure 1.** Casting configuration of (a) GBA and (b) GBAB

**Figure 2.** Test setup for bending test
3. Results and discussion

3.1. Load – midspan deflection relationship

The load during the testing is obtained by the reading of the load cell that was connected to the data logger. The rupture condition was obtained by observing the beam surface during the testing. The first rupture occurred at the midspan of all of the RC beam which confirmed that the beams underwent the failure in flexure. The load-deflection interaction of beams is displayed in Figure 3.

Figure 3. Load – deflection of FGC beams and conventional beams

The resulting loads at rupture, yield point, and ultimate condition are presented in Table 2 and Table 3.

Table 2. Load at rupture, yield, and ultimate condition

| Specimens | Load (kN) | Rupture | Yield | Ultimate |
|-----------|-----------|---------|-------|----------|
| NA1       | 10.81     | 31.22   | 39.39 |
| NA2       | 8.56      | 30.50   | 39.45 |
| Average   | 9.68      | 30.86   | 39.42 |
| NB1       | 10.58     | 32.35   | 42.28 |
| NB2       | 12.30     | 32.42   | 41.11 |
| Average   | 11.44     | 32.29   | 41.70 |
| GBA1      | 9.60      | 32.19   | 39.19 |
| GBA2      | 11.29     | 31.51   | 42.41 |
| Average   | 10.45     | 31.85   | 40.80 |
| GBAB1     | 11.12     | 32.59   | 40.59 |
| GBAB2     | 10.81     | 31.28   | 41.68 |
| Average   | 10.97     | 31.94   | 41.14 |

Table 3. Maximum load ratio

| Specimens | NA load difference (kN) | % | NB load difference (kN) | % | GBA load difference (kN) | % |
|-----------|-------------------------|---|-------------------------|---|-------------------------|---|
| GBA       | 1,38                    | 3,50 | -0,90                   | -2,16 | -                       | - |
| GBAB      | 1,72                    | 4,36 | -0,56                   | -1,35 | 0,34                    | 0,83% |
Table 3 shows that the addition of a concrete layer in FGC beams (GBAB) increases the load-carrying capacity by 0.83% as compared with the GBA and by 4.36% as compared with the NA. The present of the higher concrete strength in tensile fibre increases the bond strength and increase the beam resistant to cracking. The resulting midspan deflection at rupture, yield point, and ultimate condition are presented in Table 4 and Table 5.

### Table 4. Midspan deflection at rupture, yield, and ultimate condition

| Specimens | Rupture (mm) | Yield (mm) | Ultimate (mm) |
|-----------|--------------|------------|---------------|
| NA1       | 1.31         | 9.22       | 87.65         |
| NA2       | 1.20         | 9.33       | 58.41         |
| Average   | 1.26         | 9.28       | 73.03         |
| NB1       | 0.74         | 4.95       | 34.07         |
| NB2       | 0.94         | 6.92       | 35.14         |
| Average   | 0.84         | 5.94       | 34.61         |
| GBA1      | 0.95         | 12.76      | 59.90         |
| GBA2      | 1.11         | 7.50       | 56.09         |
| Average   | 1.03         | 10.13      | 58.00         |
| GBAB1     | 1.13         | 6.41       | 41.87         |
| GBAB2     | 0.56         | 6.71       | 38.89         |
| Average   | 0.85         | 6.56       | 40.88         |

### Table 5. Maximum deflection ratio

| Specimens | NA | NB | GBA |
|-----------|----|----|-----|
|           | Deflection difference (mm) | % | Deflection difference (mm) | % | Deflection difference (mm) | % |
| GBA       | -15.03 | -20.58 | 23.39 | 67.58 | - | - |
| GBAB      | -32.15 | -44.02 | 6.27  | 18.12 | -17.12 | -29.52 |

Table 5 shows that the GBAB reduces the midspan deflection by 29.52% as compared with the GBA. The higher concrete strength on tensile fibre contributes to the increase of structural stiffness and to strengthen the resistant of deflection.

3.2. Beam stiffness

The beam stiffness was analysed from the load-deflection relationship of each beam specimens. The beam stiffness is calculated by dividing load to deflection at each stage of failure, which was at rupture, yield, and ultimate condition. Table 6 shows the resulting beam stiffness on each failure stage. Table 6 shows that the more percentage of higher concrete strength in structural members, it increases the resulting stiffness during rupture, yield, and ultimate condition. The highest stiffness was found at the NB regarding it was cast using a full 30 MPa concrete mix. For the FGC specimens, the highest stiffness was on the GBAB due to the use of 2 layers of 30 MPa mix on outer fibre that improve the structural rigidity. The beam stiffness is incrementally decreasing as the crack propagate and reducing the moment inertia of beam cross-section.
### Table 6. Beam stiffness at rupture, yield, and ultimate condition

| Specimens | Rupture (kN/mm) | Yield (kN/mm) | Ultimate (kN/mm) |
|-----------|-----------------|---------------|------------------|
| NA1       | 8.25            | 3.39          | 0.48             |
| NA2       | 7.13            | 3.27          | 0.68             |
| Average   | 7.69            | 3.33          | 0.58             |
| NB1       | 14.3            | 6.54          | 1.24             |
| NB2       | 13.09           | 4.68          | 1.17             |
| Average   | 13.69           | 5.61          | 1.21             |
| GBA1      | 10.11           | 2.52          | 0.65             |
| GBA2      | 10.17           | 4.2           | 0.76             |
| Average   | 10.14           | 3.36          | 0.71             |
| GBAB1     | 9.84            | 5.08          | 0.97             |
| GBAB2     | 12.87           | 4.66          | 1.04             |
| Average   | 11.35           | 4.87          | 1.01             |

3.3. **Moment – curvature relationship**

Moment – curvature represents the incremental curvature of structures when a bending moment is applied. For this research, the graph of moment-curvature is generated by analysing the load-deflection data obtained during experimental testing. The moment-curvature interaction of beams is presented in Figure 4.

![Figure 4. Moment – curvature relationship](image)

Figure 4 shows that the moment-curvature interaction resulted from the bending test follow the type of load-deflection data. The data show that the GBAB exhibited lesser curvature from the beginning of the loading phase until the beams failed. The GBA exhibited moment-curvature interaction that is similar to the NA.
3.4. Structural ductility
Ductility is the structural ability to withstand an inelastic response and is calculated by comparing the curvature at the ultimate point to the yield point. The curvature data is obtained from the moment-curvature relationship in the preceding part. The structural ductility of each beam is shown in Table 7.

| Specimens | Ductility |
|-----------|-----------|
| NA        | 7.87      |
| NB        | 5.83      |
| GBA       | 7.48      |
| GBAB      | 6.23      |

Table 7 shows that the addition of high strength concrete layer in the GBAB decreases the ductility of the structures by 20.06% than the GBA and alter the characteristic to more brittle in nature. The data also shows that the ductility of GBAB is comparing the ductility of NB.

4. Conclusion
The research resulted that (1) the GBAB exhibited 0.83% greater maximum loads than the GBA; (2) the GBAB deflected 29.52% lesser than the GBA; (3) the GBAB posses stiffness 12.03% greater than the GBA; (4) the GBAB exhibited higher resulting yield points and ultimate state than the GBA at the moment-curvature relationship; and (5) the GBAB was 20.06% less ductile than the GBA.

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