Effect of concrete strength configuration on the structural behaviour of reinforced graded concrete beams

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Abstract. Earlier experimental studies of graded concrete mentioned that by combining 2 (two) concrete mixes with distinguished strength, it created an advanced material with a higher modulus of elasticity. Research related to the application of graded concrete on beam elements has been conducted several times by researchers and produced numerous important findings. Research using finite element has been conducted to analyse the extensive use of graded concrete when applied to reinforced concrete beams with various configurations. This research aims to validate the findings of previous research in experimental works. Graded concrete beams made of 2 (two) layers of concrete mixes were tested. The difference between the two types of testing beams is in the configuration of concrete placement. The beams were tested under four-point bending procedure to obtain load-deflection data. The results show that the placement of higher concrete strength in the tensile fibres provides a better beam resistance to cracks indicated by an increase in the point at which the steel reinforcement experiences yielding. The greater the tensile strength of the concrete, the concrete will provide a better bonding to the steel reinforcement so that cracks can be minimized. A concave pattern is found in the transition area after the first crack. A noticeable curve pattern becomes apparent at beams composed of low concrete strength, whereas in the beam with high concrete strength only created a linear pattern. In terms of stability and structural strength, GBA has superior performance when compared to GAB. GBA tends to be able to continue to maintain the value of structural rigidity until the beam reaches the ultimate condition. Meanwhile, the GAB instantly loses its stiffness and to experience a sudden collapse.

1. Background
Research on graded concrete material has been continuously developed from both in the material and the structural scopes. Earlier experimental studies of graded concrete mentioned that by combining 2 (two) concrete mixes with distinguished strength, it created an advanced material with a higher modulus of elasticity, although the strength of the material is still determined by lowest concrete strength [1–6]. The graded concrete is expected to create more economical and functional structures [7]. The graded concrete is a distinctive type of concrete material because it has varying material properties at different positions of observation, which at least include the compressive strength, the tensile strength, the elastic...
moduli, and the Poisson's ratio. The different value in material properties will, of course, alter the structural performance than of the conventional structures.

Beams are structural elements that have an important role in a building. The beam is a flexural element which dominantly withstands bending moments and shear forces with a minimum value of axial force. In a building, the beam is responsible to support the slabs where dead loads and live loads work. The beams require an intensive design procedure to provide capacity at different loading combination schemes, good serviceability for occupants, and comply with the corresponding design codes. Research related to the application of graded concrete on beam elements has been conducted several times by researchers and produced numerous important findings. Aylie et al. [8] conducted a finite element parametric study to analyse the extensive use of graded concrete when applied to reinforced concrete beams with various configurations. The research uses 2 (two) concrete qualities, namely 60 MPa and 20 MPa, and cast with an intensive method to create graded concrete elements. The results show that the beam consisting of 3-layer configuration, namely 60-20-60 MPa, has the best performance compared to other variables, and is followed by beams 60-20MPa, 20-60MPa, 20-60-20 MPa, respectively. Further, the research results of Han et al. can be seen in Figure 1.

![Graph](image)

**Figure 1.** Research findings of Aylie et al. [8]

Further research was carried out by Han et al. [9] which stated that the application of graded concrete in multi-story building beam elements does not compensate for significant additional material to fulfil the building code requirement. The graded concrete beams require only 2.3% additional rebars. Studies using a finite element approach also confirm that the use of graded concrete in beams can improve the performance as indicated by the moment-curvature of the beam compared to the normal concrete beams [10]. Furthermore, Pratama [11] also states that graded concrete beams have better shear resistance than conventional reinforced concrete beams, as evidenced by experimental studies and finite element analysis using ABAQUS.

Recent research conducted by Pratama [12] shows that graded concrete beams consisting of 3 (three) layers of concrete mix configurations, shows a structural behaviour that is practically higher than that of graded concrete beams consisting of 2 (two) layer configurations. Moulding a higher concrete strength on tensile fibre and compressed fibre increases the bonding strength of concrete to the reinforcement bars simultaneously with increasing the concrete's resistance to compressive stress. With such a scenario, the concrete beam also has a higher cracking resistance so that the beam is better at withstanding the designed loads.
This research aims to validate the findings of Aylie et al. [8]. Two graded concrete beams made of 2 (two) layers of concrete mixes were tested. The difference between the two types of testing beams is in the configuration of concrete placement. Beam GBA is composed of high strength concrete placed on compression fibre, the lower strength concrete on tensile fibre; and the other beams, GAB, have the opposite configuration. This research is expected to study the behaviour of the two beams tested under flexural test. GBA and GAB beams were experimentally tested using the four-point bending along with reference specimens.

2. Method
This research was conducted experimentally at the Laboratory of Structures, Universitas Negeri Malang. The beam design and the specimen test setup in this study followed the research of Pratama [11,12]. The beam was designed to experience failure in flexure by taking into account the ratio of the beam span to the effective height of more than 2.5. The beam was designed to have a 700 mm of observation area from a total span of 2200 mm. To provide good stability, the beam was featured with doubly reinforced and shear reinforcement.

Test specimens in this study are divided into 2 (two) types, namely control specimens and test specimens. The control specimen consisted of samples of rebars, cylindrical concrete samples, and reference beams of 25 MPa (RA) and 30 MPa (RB). The test specimens consisted of graded concrete beams that had greater strength at the bottom fibre, and lower strength in top fibre (GAB); and that had greater strength at the top fibre, and lower strength in bottom fibre (GBA). The illustration of graded concrete beams is demonstrated in Figure 2.

![Figure 2. Graded concrete beams: (a) GAB; and (b) GBA](image)

3. Results and discussion

3.1. Tensile test on reinforcing steels
The testing of rebars was carried out on reinforcement samples which are used as reinforcement in beam specimens. The rebar was divided into 2 (two) types, namely the 10 mm in diameter for the longitudinal bars, the 6 mm in diameter for shear reinforcement. Each type of reinforcement was prepared by a sample of 3 pieces. The test aims to determine the yield stress and the ultimate stress of each sample. The test results are shown in Table 1.
Table 1. Result of uniaxial tensile test on reinforcing steels

| Diameter (mm) | Sample Code | Yield stress (MPa) | Ultimate stress (MPa) | Average yield stress (MPa) | Average ultimate stress (MPa) |
|---------------|-------------|-------------------|----------------------|---------------------------|-------------------------------|
| Ø6            | 6.1         | 311.42            | 425.98               | 305.81                    | 416.35                        |
|               | 6.2         | 311.42            | 418.04               |                           |                               |
|               | 6.3         | 294.60            | 405.03               |                           |                               |
| D10           | 10.1        | 330.48            | 454.00               | 340.62                    | 476.23                        |
|               | 10.2        | 343.77            | 484.22               |                           |                               |
|               | 10.3        | 347.62            | 490.48               |                           |                               |

3.2. Compression test on cylindrical concrete samples
Compressive testing on cylindrical concrete samples aims to determine the compressive strength characteristics of each concrete mix. The graded concrete beams designed in this study were composed of 2 (two) varying concrete strength, namely 25 MPa and 30 MPa. The concrete mixes that have been freshly made are moulded in beam formworks and cylindrical concrete moulds to determine the actual compressive strength. Each concrete mix was cast in 3 (three) samples and tested at the age of 28 days. The result of the concrete compression test is shown in Table 2.

Table 2. Result of concrete compression test

| Concrete strength | Sample Code | Compressive strength (MPa) | Average compressive strength (MPa) |
|-------------------|-------------|-----------------------------|-----------------------------------|
| 25 MPa            | A1          | 20.94                       | 24.56                             |
|                   | A2          | 26.47                       |                                   |
|                   | A3          | 26.25                       |                                   |
| 30 MPa            | B1          | 37.17                       | 31.50                             |
|                   | B2          | 27.16                       |                                   |
|                   | B3          | 30.16                       |                                   |

3.3. Load-deflection interaction
Data obtained from the flexural test of beams is load incrementation generated from load cell reading, and vertical deflection originating from transducers mounted in the centre of the beam span. In this study, the data reading is computerized except for the reading of transducers that was done through direct observation. Figure 3 shows a recapitulation of the load to deflection relationship from RA, RB, GAB, and GBA. The discussion will be carried out in three stages, namely at the point where the first crack occurred, at the point where the tensile rebars yield, and at the peak point where the beam showed its maximum capacity. The test results show that when the first crack condition, the load achieved by the RA, RB, GAB, and GBA beams were 8.5 kN, 10.6 kN, 11.3 kN, and 11.3 kN; while the deflection that occurred was 1.2 mm, 0.7 mm, 1.2 mm and 1.1 mm, respectively. In the condition of tensile reinforcement experiencing yielding, the load achieved by the RA, RB, GAB, and GBA beams were 30.5 kN, 32.3 kN, 31.6 kN, and 31.5 kN respectively; while recorded deflections in were 9.3 mm, 5.0 mm, 6.1 mm and 7.5 mm. Lastly, in the ultimate condition, the load achieved by the RA, RB, GAB, and GBA beams were 39.5 kN, 42.3 kN, 40.9 kN, and 42.4 kN, while the deflections recorded in that condition are 58.4 mm, 34.1 mm, 49.5 mm and 56.1 mm, respectively.

The data shows that both GAB and GBA have the same load performance at the first crack, which is 11.3 kN. The beam resistance to the rupture is closely related to the thickness of the concrete cover on
the tensile fibres and the distribution of the concrete constituent materials in the concrete cover. The greater the concrete cover, the greater the beam resistance to the risk of cracking due to tensile stress [13]. The reason for identical load performance in both graded concrete beams is because the thickness of the concrete cover in GAB is predicted to be smaller than in the GBA. The GAB that possesses the greater concrete strength in the tensile fibre should provide a greater rupture resistance when compared to GBA if both have the same thickness of the concrete cover. The factor affecting the difference in thickness of the concrete covers on the two beams is the lack of control over the concrete blocks used. Concrete decking used in GAB is less than designed to create an inadequate cover. A better-quality control is needed to create more perfect specimens detailing. Another factor causing the bias data is non-uniformly distributed concrete constituent materials on the concrete cover. Concrete is a heterogeneous material because it is composed of materials with various sizes and characteristics. Potential of material separation is very possible to occur because of the characteristics of the concrete mixture and the handling method. When concrete placing, it is possible that only the concrete matrices fill the concrete cover without the presence of coarse aggregates. It is because the beam specimens only have a blanket thickness of 15 mm and there is a congestion of rebars. These conditions cause the coarse aggregates to be held above the reinforcement and unable to pass through to fill the concrete cover space. Also, the coarse aggregate used in this study has a size of 20 mm which is larger than the size of concrete cover. Other reason being, the mixtures of 25 MPa and 30 MPa concrete also have insignificant strength differences so that the proportion of the constituent materials does not differ much. These reasons support the finding that the load achievements at the first crack condition on both GBA and GAB have no difference.

![Figure 3. Recapitulation of the load to deflection relationship from RA, RB, GAB, and GBA](image)

At yield stage, the GBA was found to reach a load that is 0.2% lower than the GAB. There are no significant differences between the two types. The performance of beams in this phase is determined by the strength of concrete material in the tensile fibre, the strength of the steel in the tensile fibre, and the strength of the concrete in the compressive fibre. The greater the strength of the concrete in the tensile fibres, then the beam resistance in holding the propagation of cracks to the compressive fibres is also greater [14]. Although the contribution of the tensile strength of concrete does not dominate, the greater the tensile strength of the concrete, the concrete will provide a better bonding to the steel reinforcement so that cracks can be minimized. In this condition, GAB specimens provide higher load performance than GBA. The placement of higher concrete strength in the tensile fibres provides a better beam resistance to cracks indicated by an increase in the point at which the steel reinforcement experiences
yielding. It is necessary to consider the use of significantly distinguished concrete strength in the tensile and compression fibres to understand the performance of the beam structures.

At the ultimate conditions, the beam's performance is determined by the characteristics of concrete in the compressive fibre, the steel in the compressive fibre, and the behaviour of post-yield of the steel in the tensile fibre. After the tensile reinforcement is yielding, the tensile stress that occurs in the beam utilizes the behaviour of rebars in the hardening and necking phase. This phase is a fairly long phase, where the beams do not exhibit a significant increase in load, and only experience a great deflection before collapse due to loss of stiffness. The greater the ability of steel in experiencing a large strain increase, the beam has a high level of ductility characterized by a large ultimate deflection. Along with the reinforcing steels in the tensile fibre experiences a great value of strain, the cracks continue to enlarge and to spread along the neutral axis towards the compression fibre of the beams. The upper side of the cross-section which initially experienced compressive stress will gradually experience tensile stress due to the crack. The higher the strength of concrete at the top of the beam, the higher the crack resistance produced. This analogy is proven in the test results which show that GBA which has a higher concrete strength in compression fibre has an ultimate load of 3.7% greater than GAB.

3.4. Beam stiffness
Beam stiffness under elastic conditions is obtained by comparing the value of the load to deflection when the beam experiences the first crack. Stiffness is a property of structural elements that are closely related to the level of service of structures. The higher the stiffness of structural elements, the higher the level of serviceability produced. Structural stiffness is a linear function of the strength of concrete materials [15]. The higher the strength of the concrete, the higher the rigidity produced. The elastic stiffness of NA, NB, GBA, GAB specimens were 7.2 kN mm\(^{-1}\), 14.3 kN mm\(^{-1}\), 9.8 kN mm\(^{-1}\), and 10.2 kN mm\(^{-1}\), respectively. The results show that the NB which is composed of the highest concrete strength has the highest rigidity, while the NA which is composed of the lowest concrete strength has the lowest rigidity. In graded concrete beams, GAB has a greater stiffness value than GBA. Although GAB shows the same load as GBA when the first crack occurs, the deflection that occurs in GAB is smaller so that the resulting stiffness calculation becomes greater.

A concave pattern is found in the transition area after the first crack. A noticeable curve pattern becomes apparent at beams composed of low concrete strength, whereas in the beam with high concrete strength only created a linear pattern. In the GBA, a concave pattern with a curvature similar to RA is formed. The greater the curvature pattern means there is a big gap of material moduli so the stress transfer from the concrete to the tensile reinforcement is pronounced. In the case of GAB, a concave pattern is not found, as is the case with RB. Because the modulus of elasticity ratio of the concrete in tensile fibre to the tensile rebars is not as large as in GBA or NA, only a decrease in stiffness is found after rupture. After the stress transfer mechanism, the relationship between the load and the beam deflection becomes linear. In this phase, it appears that GAB has a more upright slope than GBA, indicating that the GAB beam has a greater stiffness than GBA after rupture. The correlation obtained from this finding is if the beam has cracked and the tensile reinforcement starts to withstand the working stress, GAB has better structural reliability.

After the rebars yield, it appears that GAB experiences less stable load and deflection behaviour compared to GBA. These findings are supported by fluctuations in data on GAB while GBA tends to continue to behave linearly and continue to increase. When related to stability and structural strength factors, in this case, GBA has superior performance when compared to GAB. GBA tends to be able to continue to maintain the value of structural rigidity until the beam reaches the ultimate condition. The minus point found in GAB is that after achieving the ultimate condition, the beam instantly loses its stiffness and to experience a sudden collapse. If this type of structural element is applied to a building, the collapse of the building is inevitable. A good structural element is an element that can maintain its rigidity even if it passes the peak load condition.

3.5. Cracks observation
This section will compare the crack pattern found in each of the control specimens and the test specimens. During the testing, the specimen was placed on simple support and a four-point bending test is applied. A spreader is placed in the centre of the span to create a pure bending observation area without being interrupted by shear forces. Overall, RA, RB, GAB, and GBA experience flexural failure, characterized by the formation of vertical cracks in the flexural area which are initiated in the middle span of the beam. The vertical crack continues to spread upward as the load is applied. The first crack position occurs in the middle of the span, then spreads to the left and right side of the first crack. The cracks were found precisely in the position where shear reinforcement was installed as there was the minimum thickness of the concrete cover.

Considering that the a to d of the beam is designed to be 2.6, the failure that occurs in the beam is not in pure bending; but at the beginning of loading, the beam will experience flexural failure characterized by vertical cracking, and it ends up with the formation of diagonal cracks outside the bending area near the point of loading. All specimens are found in a similar pattern of failure. A non-symmetrical deflection is found in RB and GAB specimens. The formation of the failure began to occur at the beginning of the loading stage which continued until the end of testing so that the asymmetrical shape becomes apparent. RB and GAB have greater concrete strength in the tensile fibre of the beam, so the load that caused the first crack in both specimens is greater than other specimens and the beam supports give a greater reaction as that condition until cracking occurs. Because of the different types of supports at the two sides of the beam, which are hinge and roller, the hinge prevents the translation in the horizontal direction while the roller provides relaxation to the beam to make a lateral translation. Of course, it makes the imbalance of confinement on the left and right span beams. These conditions require researchers to justify the deflection data obtained on the specimen.

Each specimen is tested until it experiences crushing on the compressive side of the beam so that the beam is unable to withstand any additional load and the beam will only experience deflection until the beam completely collapses. The overall failure shape of the test specimen confirms that the beam failure begins with the yielding of steel on the tensile fibre and ends with concrete crushing on the compression fibre. Details of the crack pattern of each specimen are displayed in Figure 4.

Figure 4. Crack pattern of (a) RA, (b) RB, (c) GBA and (d) GAB

4. Conclusion

- The greater the concrete cover, the greater the beam resistance to the risk of cracking due to tensile stress. The GAB that possesses the greater concrete strength in the tensile fibre should provide a greater rupture resistance when compared to GBA.
- The greater the strength of the concrete in the tensile fibres, then the beam resistance in holding the propagation of cracks to the compressive fibres is also greater because the concrete will
provide a better bonding to the steel reinforcement. In this condition, GAB specimens provide higher load performance than GBA.

- The higher the strength of concrete at the top of the beam, the higher ultimate load will be achieved.
- The higher the strength of the concrete, the higher the rigidity produced. In graded concrete beam, GAB has a greater stiffness value than GBA.
- The GAB experiences less stable load and deflection behaviour compared to GBA after the yield of rebars. These findings are supported by fluctuations in data on GAB while GBA tends to continue to behave linearly and continue to increase.
- When related to stability and structural strength factors, in this case, GBA has superior performance when compared to GAB. GBA tends to be able to continue to maintain the value of structural rigidity until the beam reaches the ultimate condition.
- Further studies are required to investigate the resulting flexural behaviour of graded concrete beams using: 1) variation of concrete strength disparity on top and bottom fibre; 2) numbers of depth to width ratio of beam’s cross-section; and 3) singly- and doubly-reinforced in the longitudinal span.

Acknowledgement
This work was supported by PNBP research grant of Universitas Negeri Malang

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