Analysis of flexural capacity in hybrid high strength reinforced concrete beams with additive, fine aggregate, and coarse aggregate substitutions

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Abstract. High-strength concrete is formed with a low water-cement ratio value, so it requires large amounts of cement, aggregate, and additives (silica fume) and admixture superplasticizer. Therefore it is necessary to do further research on the use of additional substitute materials. This study aims to analyze the flexural capacity of high-strength hybrid concrete beams using materials from Charcoal combustion fly ash, palm, pozzolanic sand, and hematite nanomaterials as additives and aggregate substitutions. In this study, 7 beams measuring 15 x 30 x 220 cm were tested for each additive variation and aggregate substitution of one specimen and one normal beam specimen. The test object is designed to experience flexural failure. The results showed that all beams failed flexibly as planned. The highest flexural capacity in reinforced concrete beams with additive variation of Charcoal fly ash and substitution of palm shell fine aggregate (BBMTH BB - KCS) is 257.707 KN or 14.217% higher than reinforced concrete beams without additive and substitution variations (BBMTH Normal) with a value of flexural capacity of 225.628 KN. It can be concluded that additive variation and aggregate substitution can increase the value of flexural and deflection capacity but are unable to add ductility values to high-strength hybrid concrete.

1. Introduction

High-strength concrete can be interpreted as high strength concrete which considers the durability of the concrete as well as the ease of workability. Based on SNI PdT-04-2004-C, high-strength concrete is concrete with required compressive strength, f',c, of 40 MPa - 80 MPa. High-strength concrete is formed with a low water-cement ratio value, so it requires large amounts of cement, aggregate, and additives (silica fume) and admixture superplasticizer. Concrete strength improvement can be done by adding or substituting other materials (additives) into the concrete mixture.

In this study, researchers substituted cement, fine aggregates and coarse aggregates on high-strength concrete mixtures with charcoal fly ash, palm oil clinkers, pozzolanic sand, and added hematite nanomaterials as fillers. As previously investigated in the shear capacity experiment of high-strength reinforced concrete beams using geopolymers fly ash [1], this study will review the flexural capacity of high-strength hybrid reinforced concrete beams.

The purpose of this study was to determine the flexural capacity of high-strength reinforced concrete beams using alternative materials, namely charcoal fly ash, palm shell chunks and pozzolanic sand instead of cement, fine aggregates and coarse aggregates and the additive of hematite nanomaterial.
fillers. In addition, the ductility and crack beam destruction patterns of the high-strength reinforced concrete beams that use a combination of variations in cement substitution, fine aggregate, and coarse aggregate were compared to those of the high-strength reinforced concrete beams without variation (normal).

2. Methodology

2.1. High-strength concrete
High-strength concrete criteria change through times and progress in strength levels. In the 1950s, concrete was categorized as high-strength if the compressive strength was 30 MPa, but from 1960 to 1970, the criteria rose to 40 MPa. At present, the concrete is said to be of high-strength concrete if its strength above 55 MPa, to be of very high-strength if the strength is above 80 Mpa, and to be of ultra high-strength if the strength is above 120 MPa [2].

2.2. Additional materials on concrete
The use of additional materials is intended to improve and add the properties of the material in accordance with the desired concrete properties. Additional materials used in concrete can be divided into two, namely chemical additives or chemical admixture and mineral additives, known as additives. Additives are added to improve the performance of concrete strength, while admixture functions for the ease of the work (workability). Admixture is added during stirring and when the casting is carried out [2].

2.3. Flexural beam analysis
The flexural analysis of multiple reinforced concrete blocks involves determining the nominal moment strength of a cross-section (Mn) with values a, b, d, d’, As, As2, f´c and fy, which can be written with the following equation [3]:

\[ M_{n1} = A_s \cdot f_y \left[ d - \frac{a}{2} \right] \]  (1)

\[ M_{n2} = A_s' \cdot f_y (d - d') \]  (2)

\[ M_n = M_{n1} + M_{n2} \]  (3)

ergo:

\[ a = \frac{A_s \cdot f_y \cdot 0,85 \cdot f'_c \cdot b}{C} \]  (4)

\[ C = \frac{a}{\beta} \]  (5)

Information:

\( M_n \) = Nominal strength of flexural moment (kg.cm),

\( a \) = High block compressive voltage (cm),

\( C \) = The distance of the outer fiber to the neutral line (cm),

\( d \) = Distance from the outermost fiber to the center of the tensile reinforcement (cm), and

\( d' \) = Distance from the outermost fiber to the center of the compressive reinforcement (cm).

2.4. Planning high-strength hybrid reinforced concrete beam planning
Based on the analysis carried out to obtain specimens that failed to resist flexural, the size and number of reinforcement were obtained, as shown in table 1. The planned specimens were hybrid high-strength
reinforced concrete blocks with additional materials and aggregate substitution in the form of charcoal fly ash, palm oil clinkers, sand pozzolan, and hematite nanomaterial with 70 MPa plan strength. The beam used is 15 cm x 30 cm x 220 cm.

Table 1. Size and amount of reinforcement of beam test items.

| Test object | Basic Reinforcement | | Reinforcement | Total |
|-------------|---------------------|-----|---------------|-------|
|             | Compressive | Tensile | Shear |       |
| Hybrid high-strength concrete (BBMTH) | 2 D 11.9 | 4 D 15.8 | D 11.9 - 100 | 7 |

2.5. Concrete mixing planning
The composition plan of the concrete mix (concrete mix design) was based on the method of comparing the volume weight of the concrete forming material. For the design of this high-strength hybrid concrete mixture, it is planned to have 70 MPa concrete strength with 0.3 water-cement ratio. The composition of the hybrid high-strength concrete (BBMTH) plan can be seen in the following table 2.

Table 2. Composition of hybrid high-strength concrete.

| Test Object (TO) | Cement (100%) | Fine aggregate (100%) | Coarse aggregate (100%) | Nanomaterial hematite 6% as filler |
|-----------------|----------------|-----------------------|-------------------------|----------------------------------|
| TO 2 BBMTH BB-PP | Charcoal Fly ash (15%) | Cement (85%) | Pozzolanic sand (10%) | Fine aggregate (90%) | Palm oil clinker coarse aggregate (40%) | Coarse aggregate 60% | Nanomaterial hematite 6% |
| TO 3 BBMTH BB-KCS | Charcoal Fly ash (15%) | Cement (85%) | Fine palm oil clinker aggregate (20%) | Fine aggregate (80%) | Palm oil clinker coarse aggregate (40%) | Coarse aggregate 60% | Nanomaterial hematite 6% |
| TO 4 BBMTH AP-PP | Pozzolanic fly ash (10%) | Cement (90%) | Pozzolanic sand (10%) | Fine aggregate (90%) | Palm oil clinker coarse aggregate (40%) | Coarse aggregate 60% | Nanomaterial hematite 6% |
| TO 5 BBMTH AP-KCS | Pozzolanic fly ash (10%) | Cement (90%) | Fine palm oil clinker aggregate (20%) | Fine aggregate (80%) | Palm oil clinker coarse aggregate (40%) | Coarse aggregate 60% | Nanomaterial hematite 6% |
| TO 6 BBMTH CS-PP | Palm oil clinker fly ash (15%) | Cement (85%) | Pozzolanic sand (10%) | Fine aggregate (90%) | Palm oil clinker coarse aggregate (40%) | Coarse aggregate 60% | Nanomaterial hematite 6% |
| TO 6 BBMTH CS-KCS | Palm oil clinker fly ash (15%) | Cement (85%) | Fine palm oil clinker aggregate (20%) | Fine aggregate (80%) | Palm oil clinker coarse aggregate (40%) | Coarse aggregate 60% | Nanomaterial hematite 6% |
2.6. Testing of objects
This test aims to obtain data on the maximum load that can be held by beams, strain, and deflection that occur. Steel and concrete deflection and strain are monitored for every 100 kg load increase using the LVDT (transducer) and strain gauge. The test set for BBMTH beam flexural capacity can be seen in the following picture.

![Diagram of testing setup](image)

**Figure 1.** Strength testing of reinforced concrete.

3. Results and discussion

3.1. Compressive strength and flexural tensile strength
Based on figure 2, it can be seen that the value of the compressive strength of the BMTH control cylinder with additive variation and aggregate substitution having mixed results when compared with the value of compressive strength in Normal BBMTH. BBMTH BB - PP, BBMTH, BB - KCS BBMTH AP - PP, and BBMTH AP - KCS have higher compressive strength values than Normal BBMTH whereas the last two specimens, namely Normal CS - PP and BBMTH CS - KCS have lower compressive strength values. However, the compressive strength of BBMTH CS - PP and BBMTH CS - KCS can still be classified as high-strength concrete [3].

![Compressive Strength Graph](image)

**Figure 2.** Compressive strength of concrete cylinder testing.
In contrast to compressive strength, flexural tensile strength BBMTH additive variation and aggregate substitution have uniform results. This can be seen in figure 3. The value of flexural tensile strength is higher than that of Normal BBMTH. The average maximum load produced in this flexural tensile strength test is used as a reference to determine the initial cracks in BBMTH beams and serve as a reference during testing.

Based on the previous analysis on BBMTH with additive variation and aggregate substitution, the value of compressive strength is not always followed by the value of the BBMTH flexural tensile strength itself. In other words, in this case, the relationship of the value of compressive strength with flexural strength is not linear. The results obtained are in accordance with the research which states that the relationship between the compressive strength of the flexural strength of the concrete is always parabolic [4]. This means that at a certain point, the increase in the value of concrete compressive strength will be accompanied by an increase in the flexural strength of the beam, but at certain points, it shows the opposite result.

3.2. Load and deflection
The comparison of load and deflection of BBMTH with additive variation and aggregate substitution can be seen in figure 4. In figure 4, it can be seen that the graphs of BBMTH AP - PP and BBMTH CS - KCS are more sloping compared to the other five graphs. This shows that the high-strength hybrid reinforced concrete beams with a variety of additional materials have a smaller flexural capacity value compared to the other five beams. The results of the graph reading for the loading area at the initial crack, transitional load, and ultimate load, can be seen in table 3.

Comparison of BBMTH beam deflection with additive variation and aggregate substitution on BBMTH Normal beams can be seen in table 4. It can be seen from the deflection value in the table, BBMTH beams with additive variation and aggregate substitution can increase the value of high-strength concrete beam deflection. In general, the largest increase in deflection values occurs in BBMTH beams with additive variations of fly ash pozzolan (code: AP). The increase in the highest deflection value is in the BBMTH AP - PP beam, which is equal to 252.157% of the deflection of Normal BBMTH. This is because the fly ash pozzolan has a small grain diameter so that the spread in the mixed matrix is more evenly distributed. The increase in deflection that occurs in BBMTH with additive variation and aggregate substitution varies greatly between 104.575% - 252.157%.

| Tested Object Variations | Flexural Tensile Strength (MPa) |
|---------------------------|---------------------------------|
| BB-PP                     | 5.35                            |
| BB-KCS                    | 5.04                            |
| AP-PP                     | 5.40                            |
| AP-KCS                    | 5.18                            |
| CS-PP                     | 5.73                            |
| CS-KCS                    | 5.52                            |
| BMTH with Variations and Substitutions | 4.5                            |

Figure 3. Strength testing of flexural concrete beams.
Figure 4. Comparison chart of the relationship between load - concrete deflection.

Table 3. Results of reading deflection charts.

| Beam Test Objects | First crack | Transition | Maximum Load |
|-------------------|-------------|------------|--------------|
|                   | P (ton) | Deflection (mm) | P (ton) | Deflection (mm) | P (ton) | Deflection (mm) |
| BBMTH-N           | 7.550 | 1.750 | 22.830 | 3.450 | 23.000 | 7.650 |
| BBMTH BB-PP       | 4.550 | 0.900 | 19.580 | 9.250 | 23.070 | 15.650 |
| BBMTH BB-KCS      | 5.100 | 2.500 | 22.650 | 9.250 | 26.270 | 18.500 |
| BBMTH AP-PP       | 3.030 | 0.430 | 20.140 | 7.060 | 22.960 | 26.940 |
| BBMTH AP-KCS      | 4.100 | 0.910 | 21.480 | 10.100 | 23.100 | 24.530 |
| BBMTH CS-PP       | 3.380 | 2.840 | 19.860 | 8.300 | 23.380 | 16.440 |
| BBMTH CS-KCS      | 6.590 | 3.460 | 19.690 | 12.170 | 20.960 | 18.710 |

Table 4. Comparison of BBMTH N beam deflection with BBMTH beams additive variations and aggregate substitution.

| Beam Test Objects | Theoretical deflection (mm) | Deflection at the P Ultimate (mm) | Comparison of Deflection Against Normal Deflection BBMTH |
|-------------------|-----------------------------|----------------------------------|--------------------------------------------------------|
|                   |                             |                                  | Percentage (%) | Difference (%) |
| BBMTH-N           | 17.02                       | 7.650                           | 100.000        | -             |
| BBMTH BB-PP       | 17.74                       | 15.650                          | 204.575        | 104.575       |
| BBMTH BB-KCS      | 18.68                       | 18.500                          | 241.830        | 141.830       |
| BBMTH AP-PP       | 17.74                       | 26.940                          | 352.157        | 252.157       |
| BBMTH AP-KCS      | 18.44                       | 24.530                          | 320.654        | 220.654       |
| BBMTH CS-PP       | 16.53                       | 16.440                          | 214.902        | 114.902       |
| BBMTH CS-KCS      | 15.79                       | 18.710                          | 244.575        | 144.575       |
3.3. Concrete load and strain

Based on figure 5, it can be seen that the Normal BBMTH Beams have a concrete strain of 197.650 με at a load of 23.00 tons. The BBMTH BB - PP beam has a concrete strain of 218.742 με at a load of 23.07 tons. The BBMTH BB - KCS beam has a concrete strain of 106.017 με at a load of 26.27 tons. BBMTH AP - PP beam has a concrete strain of 78.153 με at a load of 22.96 tons. BBMTH AP - KCS beam has a concrete strain of 64.656 με at a load of 20.96 tons.

![Comparison Chart of Relationship Between Loads - Concrete Strains](image)

**Figure 5.** Comparison chart of the relationship between loads - concrete strains.

3.4. High-strength hybrid concrete reinforced capacity (BBMTH)

The BBMTH beam test results are shown in table 5 below.

| Beam Test Objects | f’c (Mpa) | Maximum Load (KN) | Flexur Moment (KN.m) |
|-------------------|----------|-------------------|----------------------|
|                   | Pu Teoritis | Plab | Plab/Pu | Mn Teoritis | Mlab | Mlab/Mn |
| BBMTH-N           | 61.115   | 206.697 | 225.628 | 1.092 | 72.344 | 86.539 | 1.196 |
| BBMTH BB-PP      | 64.511   | 207.721 | 226.315 | 1.090 | 72.702 | 86.387 | 1.188 |
| BBMTH BB-KCS     | 69.038   | 208.988 | 257.707 | 1.233 | 73.146 | 96.589 | 1.320 |
| BBMTH AP-PP      | 64.511   | 207.721 | 225.236 | 1.084 | 72.702 | 86.345 | 1.188 |
| BBMTH AP-KCS     | 67.906   | 208.681 | 226.609 | 1.086 | 73.038 | 86.462 | 1.184 |
| BBMTH CS-PP      | 58.852   | 205.973 | 229.356 | 1.114 | 72.090 | 87.031 | 1.207 |
| BBMTH CS-KCS     | 55.457   | 204.816 | 205.616 | 1.004 | 71.686 | 78.890 | 1.100 |

From table 5, the highest increase in flexural capacity in BBMTH with additive variation and aggregate substitution on BBMTH Normal, i.e., on the BBMTH BB-KCS specimen with a value of 257.707 KN, increased by 14.2% from Normal BBMTH at 225.688%. From table 5, it can be seen that the Plab ratio ranges from 1.084 to 1.233Pu. This explains that the laboratory results are in accordance with the theoretical results which are calculated by the difference in a difference of 8.4% - 23.3%. While from
Table 6, it can be seen that the theoretical comparison ratio between Shifts to Plots is more than 1 (Placement < Shift). This is in accordance with the initial planning regarding the behavior of the BBMTH beam with variations and planned substitutions which failed to flex.

Table 6. Comparison of flexural and shear loads of theoretical calculation results.

| Beam Test Objects | $f'_c$ (Mpa) | Based on the Preliminary Design of Beam Cross Section Capacity | Ratio |
|-------------------|-------------|-------------------------------------------------------------|-------|
|                   |             | Flexural Strength                                          |       |
|                   |             | Moment (kNm)      | P Flexural (kN) | P Shear (kN) | Theoretical Deflection (mm) | (P Shear / P Flexural) |
| BBMTH-N           | 61.115      | 72.344           | 206.697        | 557.293     | 17.018                      | 2.6962           |
| BBMTH BB-PP       | 64.511      | 72.702           | 207.721        | 559.794     | 17.737                      | 2.6949           |
| BBMTH BB-KCS      | 69.038      | 73.146           | 208.988        | 563.047     | 18.675                      | 2.6942           |
| BBMTH AP-PP       | 64.511      | 72.702           | 207.721        | 559.794     | 17.737                      | 2.6949           |
| BBMTH AP-KCS      | 67.906      | 73.038           | 208.681        | 562.244     | 18.443                      | 2.6943           |
| BBMTH CS-PP       | 58.852      | 72.090           | 205.973        | 555.564     | 16.531                      | 2.6973           |
| BBMTH CS-KCS      | 55.457      | 71.686           | 204.816        | 552.927     | 15.788                      | 2.6996           |

From the results of the comparison of the beam capacity with additive variation and aggregate substitution shown in table 5 and table 6, it can be concluded that high-strength concrete with additive variation and aggregate substitution can increase the high-strength concrete flexural strength.

3.5. Ductility

Based on table 7, BBMTH with additive variation and aggregate substitution does not show an increase in ductility values in BBMTH beams. The ductility of BBMTH with additive variation and aggregate substitution is lower when compared to Normal BBMTH, which ranges from 74.089% - 87.582%. BBMTH AP - PP specimens, which have the highest ductility value, are higher when compared to Normal BBMTH; the value is 167.100% or 67.1% higher than those of Normal BBMTH.

Table 7. BBMTH beam ductility calculation.

| No. | Test Object Variations | Tear condition Load (P) | Deflection (Δy) | Ultimate condition Load (P) | Deflection (Δu) | Ductility $\mu = \Delta u/\Delta y$ | Actual Ductility for BBMTH Normal (%) |
|-----|------------------------|-------------------------|-----------------|-----------------------------|-----------------|-------------------------------------|-------------------------------------|
| 1   | BBMTH-N                | 22.830                  | 3.350           | 23.000                      | 7.650           | 2.284                               | -                                   |
| 2   | BBMTH BB-PP            | 19.580                  | 9.250           | 23.070                      | 15.650          | 1.692                               | 74.089                             |
| 3   | BBMTH BB-KCS           | 22.650                  | 9.250           | 26.270                      | 18.500          | 2.000                               | 87.582                             |
| 4   | BBMTH AP-PP            | 20.140                  | 7.060           | 22.960                      | 26.940          | 3.816                               | 167.100                            |
| 5   | BBMTH AP-KCS           | 21.480                  | 10.310          | 23.100                      | 24.530          | 2.379                               | 104.189                            |
| 6   | BBMTH CS-PP            | 19.860                  | 8.300           | 23.380                      | 16.440          | 1.981                               | 86.738                             |
| 7   | BBMTH CS-KCS           | 19.690                  | 10.310          | 20.960                      | 18.710          | 1.815                               | 79.469                             |

3.6. Crack pattern

The formation of cracks in general from each specimen varies, but the destruction that occurs is the same, namely flexural destruction or failure of flexural. This is indicated by the predominance of cracks in flexible areas.
4. Conclusion

1. BBMTH beams with additive variation and aggregate substitution increase the value of flexural and deflection capacity but generally are not able to increase the ductility value of hybrid high-strength concrete beams. The highest flexural capacity on BBMTH BB - KCS beams is 257.707 KN or 14.217% higher than Normal BBMTH with a flexural capacity value of 225.628 KN.
2. The maximum deflection for additive variation is obtained from test specimens with additive variations of fly ash pozzolan (BBMTH AP - PP) with the percentage of deflection to Normal BBMTH amounting to 252.157%.
3. The crack pattern between the BBMTH beams of additive variation and substitution indicates that the beam has failed flexibly. It is proven by cracks that occur in flexible areas, and almost no cracks occur in the support area. This is also in accordance with the calculation of the shear ratio: placement which ranges from 2.964-2.700.
4. Ductility in BBMTH beams with additive variation and aggregate substitution, in general, does not increase. The ductility of BBMTH with additive variation and aggregate substitution is lower when compared to Normal BBMTH, which ranges from 74.089%-87.582%. BBMTH AP-PP specimens that have the highest ductility value are higher when compared to Normal BBMTH; the value is 167.100% or 67.1% higher than those of Normal BBMTH.

References
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