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Effects of material properties of HFDFRCC Using recycled fine aggregate on shear strength of RC beam

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Abstract. In this study, we performed loading tests on RC beam specimens made of high-fluidity ductile-fiber-reinforced cementitious composites incorporating recycled fine aggregate with different water-binder ratios. We also performed nonlinear finite element analyses to investigate the effects of water-binder ratios and shear reinforcement bars on RC beam shear strength. Additionally, for some factors, we investigated the influence of the presence or absence of shear reinforcement bars on the shear strength of R-HFDFRCC RC beams. We found that fluctuations in the maximum load of the RC beam specimens attributable to differences in the water-binder ratio can generally be predicted if we understand the differences in the material properties (mainly compressive strength, tensile strength and ultimate tensile strain) of the tough, highly fluid cement compound materials incorporating recycled fine aggregate.

1. Introduction

In recent years, ductile-fiber-reinforced cementitious composites (“DFRCC” hereinafter) with a much better performance than existing fiber-reinforced concrete have been developed [1]. DFRCC are composites of cementitious material reinforced with fibers, which display multiple cracking characteristics and significantly improved toughness when subjected to bending, tension, and compression fracture [1]. These materials overcome the problem of the brittleness of ordinary concrete and are expected not only to significantly improve the performance and durability of concrete structural elements, but to lead to new applications: examples include use in place of conventional cementitious materials as high performance repair materials, shock absorbers, and the like. However, while actual construction examples using DFRCC have been reported [2], they are not common. The reasons include workability issues and high cost compared to other materials. Promoting the use of DFRCC in the future will require the development of new materials, including making improvements to existing materials.

Protecting the global environment during production activities poses a major challenge. In the field of concrete, significant research is being done on recycled aggregate concrete made using recycled aggregate extracted from dismantled concrete blocks. Promoting the expanded use of concrete recycling will require the development of new technologies that allow more effective use of recycled aggregate. Against this backdrop, one of the authors [3], with the goal in mind of improving the workability of DFRCC and expanding the application of recycled fine aggregate, examined the material properties of high fluidity DFRCC (“HFDFRCC” hereinafter) using fly ash as an admixture and fine aggregate as recycled fine aggregate. The results showed that the HFDFRCC incorporating...
recycled fine aggregate (“R-HFDFRCC” hereinafter) offers sufficient crack dispersion capabilities and excellent bending toughness.

In applying this kind of material in reinforced concrete (“RC” hereinafter) structures, we must identify a shear strength calculation formula capable of appropriately assessing the shear strength of RC members made from R-HFDFRCC. This, in turn, requires performing loading tests of RC members made from R-HFDFRCC. (Compressive strength, tensile reinforcement ratio, shear reinforcement ratio, and shear span ratio are regarded to affect RC member shear strength as test items.) It also requires an accumulation of experimental data based on appropriate strength controls. At the same time, applying analytical techniques, we must examine what determines the shear strength of RC members by obtaining data that cannot be obtained through internal stress state experiments.

To investigate the effects of different water-binder ratios (“W/B” hereinafter) on the shear strength of R-HFDFRCC RC beams, we performed loading tests on R-HFDFRCC RC beams of different W/B. Additionally, we performed uniaxial compression tests and trisecting point bending tests and extracted the fracture mechanics parameters that affect the R-HFDFRCC constitutive equations. Additionally, we factored these constitutive equations into the finite element method (FEM) analysis general code and analyzed the plastic deformation behavior of R-HFDFRCC RC beam specimens. For certain factors, we investigated the effects of the presence or absence of shear reinforcement bars on the shear strength of the R-HFDFRCC RC beams.

### Table 1. Concrete specimens.

| Specimen               | Water-binder ratio (%) | Sand-binder ratio (%) | Fiber volume fraction (vol.%) | Replacement ratio of fly ash (%) |
|------------------------|------------------------|-----------------------|-------------------------------|---------------------------------|
| R-HFDFRCC-40-56D       | 40                     | 40                    |                               |                                 |
| R-HFDFRCC-50-56D       | 50                     | 65                    | 3.0                           | 20                              |
| R-HFDFRCC-50-56D@150   |                        |                       |                               |                                 |
| R-HFDFRCC-60-56D       | 60                     | 90                    |                               |                                 |

### 2. Experiment method

#### 2.1. HDFRCC

TABLE I provides an overview of the R-HFDFRCC used in this study. The recycled fine aggregate (R) is a mixture of medium fine (max. aggregate dimensions: 2.5 mm; surface dry density: 2.57 g/cm³; water absorption rate: 2.96%; fineness modulus: 2.61) and very fine (max. aggregate dimensions: 0.6 mm; surface dry density: 2.55 g/cm³; water absorption rate: 4.46%; fineness modulus: 1.16). The cement was ordinary Portland cement (density: 3.16 g/cm³). The R-HFDFRCC W/B values were 40, 50, and 60%. The R-HFDFRCC material test specimens and R-HFDFRCC RC beam specimens were demolded two days after being placed, then wet-cured until the cumulative temperature inside the curing chamber reached 1,680°C (equivalent to age 56 days (56D)), at which point testing was done. We used PVA fiber (diameter: 0.2 mm, length: 18 mm, elastic modulus: 27 kN/mm², tensile strength: 975 N/mm²), and the fiber volume mixing ratio (V_f) was 3%. The admixture was high performance AE water reducing agent, separation reducing agent, and type II fly ash (density: 2.30/cm³; cement replacement ratio: 20%). The title is set 17 point Times Bold, flush left, unjustified. The first letter of the title should be capitalized with the rest in lower case. It should not be indented. Leave 28 mm of space above the title and 10 mm after the title.

#### 2.2. Material test

In this study, we performed R-HFDFRCC uniaxial compression tests, trisecting point bending tests, pull out tests, and reinforcement bar tensile tests to enable strength control of the R-HFDFRCC RC beam specimens and to extract the fracture mechanics parameters that affect the R-HFDFRCC material constitutive equation.
Table 2. Material properties.

(a) R-HFDRCC

| Specimen          | Compression | Bending | Pull-out |
|-------------------|-------------|---------|---------|
|                   | Fc (N/mm²)  | Gc (N/mm²) | Ftu,b (N/mm²) | Tu,b (N/mm²) | Lame (N/mm²) | S (mm) |
| R-HFDRCC-40-56D   | 50.4        | 64.7    | 7.15    | 2.25       | 0.0190       | 17.1   |
| R-HFDRCC-50-56D   | 35.4        | 59.7    | 6.52    | 2.25       | 0.0302       | 15.8   |
| R-HFDRCC-50-56D@150 | 35.7       | 55.8    | 6.27    | 2.28       | 0.0263       | 14.0   |
| R-HFDRCC-60-56D   | 28.6        | 53.6    | 6.34    | 1.88       | 0.0330       | 12.3   |

(b) Reinforcement

| Specimen          | Main reinforcement | Shear reinforcement |
|-------------------|--------------------|--------------------|
|                   | Ratio (%) | Young's modulus (kN/mm²) | Yield strength (N/mm²) | Ratio (%) | Young's modulus (kN/mm²) | Yield strength (N/mm²) |
| R-HFDRCC-40-56D   | 5.88      | 197                | 511                 |         |          |                |
| R-HFDRCC-50-56D   |          |                    |                     | 0.951   | 200      | 373              |
| R-HFDRCC-60-56D   |          |                    |                     |         |          |                |

The test specimens were, in the uniaxial compression tests, a 100 × 200 mm cylinder; in the trisecting point bending tests a 100 × 100 × 400 mm prism; in the pull out tests a 100 × 100 × 100 mm prism with a D-16 (SD490) reinforcement bar inserted; and, for the reinforcement bar tensile tests, a D-16 (SD490) rod-like specimen whose parallel part length was 10 times the nominal diameter or greater. The number of specimens produced per test was six for the uniaxial compression tests and the trisecting point bending tests and three for the pull out tests and reinforcement bar tensile tests.

The uniaxial compression tests were carried out by the method described in reference work [4]. The measurement objects were load, longitudinal and transverse strain at the central part of the specimen (as measured by a compression meter), and displacement between loading boards (as measured by a high sensitivity displacement meter). Additionally, the compression fracture energy (Gc) was calculated by the method described in reference works [4]-[5] (plastic deformation in reference works [4]-[5] up to 3.0 mm).

The trisecting point bending tests were carried out by the method described in reference work [6]. The measurement objects were load, displacement in the span center portion (as measured by a high sensitivity displacement meter), and curvature (as measured by a pi-shaped displacement meter). Tensile strength (Ftu,b) and ultimate tensile strain (εtu,b) were calculated by the method described in reference work [7], based on the appendix (reference) to reference work [6].

The pull out tests were carried out by the method described in reference work [8]. The measurement objects were load and degree of slip of the reinforcement bars.

The reinforcement bar tensile tests were carried out by the method described in reference work [9]. The measurement objects were load, longitudinal and transverse strain at the central part of the specimen, and degree of elongation of the reinforcement bars.

We gathered measurement data from the material tests using data loggers. TABLE II gives the material properties of the reinforcement bars and R-HFDFRCC obtained from the material tests.

2.3. RC beam load tests

Fig. 1 provides an overview of the R-HFDFRCC RC beam specimens. Fig. 2 provides an overview of the load tests. For the R-HFDFRCC RC beam specimens, with reference to reference works [10]-[11], the main reinforcement bars were D-16 (SD490), tensile reinforcement ratio (Fp)=5.88%, shear reinforcement bar D-10 (SD295A), shear reinforcement ratio (Pp)=0.951%, and specimen beam depth
(D) 180 mm × beam breadth (b) 100 mm × beam length 1,500 mm. The distance between the fulcrums (L) was 1,300 mm; the shear span length (a) 450 mm; and the distance between load points was 400 mm. The main reinforcement bars were welded to a fixed steel plate (thickness 6 mm) at both ends of the specimen. Loading was done using a 1,000 kN universal testing machine. The measurement objects were load, displacement in the span center portion (as measured by a high sensitivity displacement meter) and the main reinforcement bar, and shear reinforcement bar strain (as measured with a strain gauge). We used data loggers to gather measurement data and calculated the shear strength of RC beams of ordinary concrete using the following formula given in reference work [12].

\[
Q_{bu} = \frac{0.092 \ k_u \ k_p (18 + F_c)}{M/Q_d + 0.12} + 0.85 \sqrt{P_w \sigma_{wy}} \cdot b \ j
\]  

Here, \( Q_{bu} \) is the shear strength (N); \( k_u \): compensation factor 1.0, according to the cross-sectional dimension of the beam; \( k_p \): compensation factor 0.82F_0.23 according to the tensile reinforcement ratio; \( F_c \): concrete compressive strength (N/mm²); \( M/Q_d \): shear span ratio; \( P_w \): shear reinforcement ratio (%); \( \sigma_{wy} \): shear reinforcement bar yield strength (N/mm²); \( d \): effective beam depth (mm); \( b \): beam breadth (mm); and \( j \): distance between stress centers (mm).

3. Outline of analysis

3.1. Methods for modeling and analyzing specimens

In this study, we performed 3D nonlinear FEM analysis of loading tests for R-HFDFRC RC beam specimens. The R-HFDFRC RC beam specimens were divided into elements of the dimensions 25 × 30 × 30 mm and 40 mm for the R-HFDFRC and 6 × 30 × 30 mm and 40 mm for the fixed steel plates. Fig. 3 shows the division of the elements of the R-HFDFRC RC beam specimens. Each element is an eight-node isoparametric element; the main reinforcement bars are bond-stress slip embedded reinforcement elements. The reinforcement bars were modeled as truss elements. The solid elements and the truss elements were bonded by the interface elements [13].
With respect to the analysis method, a dead weight was initially added, after which a forced
displacement was added incrementally at the points indicated by arrows in Fig. 3. For the analysis
code, we used DIANA 9.4.4 [13], a general structural analysis program. We applied the Newton-
Raphston method as the nonlinear iterative calculation method.

3.2. Material constitutive equation
In response to R-HDFRCC fracturing, we established an equation based on the total strain on the
compressive and tension sides and assumed cracking would take place according to a distributed
cracking model that accounted for crack rotation.

The parabola of Fig. 4 gives the stress-strain relationship on the R-HDFRCC compression side. The
area surrounded by the stress descending zone is considered to be a $G_{fc}/L_c$ of elements. $G_{fc}$ is the material test result shown in Fig. 2, while $L_c$ is the diameter of a sphere having the
same volume as the element volume. We also considered the increase in compressive strength
attributable to lateral restraints proposed by Vecchio [15] et al. and the reduction in compressive
strength of cracked concrete proposed by Collins [16] et al.

A multi-linear model proposed by one of the authors [8] was applied to the stress–strain relationship
on the R-HDFRCC tension side (Fig. 5).

We applied a multilinear model between the R-HDFRCC and beam main reinforcement bars, constructed from the bond-stress slip relationship obtained in the pull test. The bond-stress at each
point on the bond-stress slip model was taken as the average value of the experiment results.
Additionally, in consideration of the bond stress slip relationship obtained from the experiments, the
slip at each point was taken to be 1/20 of the bond strength slip ($S_u$) at the first point, $S_u$ at the second
point, 2.5 times $S_u$ at the third point, and 7.5 times the third point at the fourth point. Fig. 6 shows the
bond-stress slip relationship applied between the beam main reinforcement bars and R-HDFRCC.

We applied the von Mises yield criterion as the yield criterion for the reinforcement bars. In

**Figure 4.** Compression model.  
**Figure 5.** Tension model.  
**Figure 6.** Bond stress-slip relationship.
accordance with the reinforcement bar yield strength and Young’s modulus (TABLE II), we formulated a bilinear model of the stress-strain relationship. Additionally, the rigidity of the second gradient was 1/100 of Young’s modulus.

4. Results and observations
TABLE III shows the maximum loads obtained from the R-HFDFRCC RC beam specimen loading tests and analyses.

4.1. HFDFRCC RC beam specimen load-displacement relationship
Fig. 7 shows the load-displacement relationship obtained from the R-HFDFRCC RC beam specimen loading tests. The triangle symbols superimposed on each result in the fig show the maximum loads (the same for Fig. 8). In tests without shear reinforcement bars, the maximum load was reached without the main reinforcement bar yielding, terminating in shear fracture. In tests with shear reinforcement bars, the maximum load was reached after the main reinforcement bars had yielded, resulting in fracture.

Looking at the influence of W/B {Fig. 7 (a) and TABLE III}, we see that the maximum load of R-HFDFRCC-60-56D fell by 2.88% compared to the maximum load of R-HFDFRCC-50-56D. However, although R-HFDFRCC-40-56D has a lower W/B than R-HFDFRCC-50-56D, the maximum load of R-HFDFRCC-40-56D fell by 1.80% compared to the maximum load of R-HFDFRCC-50-56D. In TABLE II above, the $F_c$ obtained from the strength control specimen is R-HFDFRCC-40-56D > R-HFDFRCC-50-56D. Here, if the R-HFDFRCC $F_c$ (in TABLE II above) obtained in the material test is substituted into formula (1) used to calculate the shear strength of RC beams using ordinary concrete and the calculations of shear stress performed, the calculation shear strength for R-HFDFRCC-40-56D is 58.7 kN, and that of R-HFDFRCC-50-56D 45.9 kN. According to reference [10], when calculating the shear strength of RC members made of multiple fine crack type fiber reinforced cementitious

![Figure 7. Load-displacement relationship (Experiment).](image)

![Figure 8. Load-Displacement relationship (Analysis).](image)

Table 3. The maximum loads obtained from R-HFDFRCC RC beam specimen the loading tests and analysis

| Specimen                  | Maximum load (kN) |
|---------------------------|-------------------|
|                           | Experiment | Analysis |
| R-HFDFRCC-40-56D          | 94.6       | 111       |
| R-HFDFRCC-50-56D          | 96.3       | 112       |
| R-HFDFRCC-50-56D@150      | 167        |           |
| R-HFDFRCC-60-56D          | 93.6       | 89.8      |
composites, we must account for the design tensile yield strength of the multiple fine crack type fiber reinforced cementitious composite (i.e., the condition that the average value of the ultimate tensile strain obtained from the uniaxial test is 0.5% or more). According to TABLE II above, the $F_{t,b}$ of R-HFDFRCC-40-56D and R-HFDFRCC-50-56D are equivalent. However, $\varepsilon_{tu,b}$ obtained from the strength control specimen is R-HFDFRCC-40-56D < R-HFDFRCC-50-56D. In addition to $F_c$ and $F_{t,b}$, the tensile toughness of R-HFDFRCC appears to have affected the maximum load of the R-HFDFRCC RC beam.

Looking at the influence of the shear reinforcement bars {Fig. 7(b) and TABLE III}, we see that the maximum load of R-HFDFRCC-50-56D@150 has increased 73.4% against that of R-HFDFRCC-50-56D. As mentioned above, the fracture of R-HFDFRCC-50-56D@150 with shear reinforcement bars is bending fracture. Under these experimental conditions, we found that making $P_o$ 0.951% caused the shear fracture to change to bending fracture.

Fig. 8 shows the load-displacement relationship obtained by analyzing the loading test R-HFDFRCC RC beam specimens. Additionally, all analysis results confirmed that the maximum load was reached without the main reinforcement bars yielding, and the experimental fracture mode proved reproducible.

In considering the effects of W/B {Fig. 8 and TABLE III} compared to the maximum loads obtained from the experiments described above, we see a strong influence with R-HFDFRCC-40-56D. This is slightly lower with R-HFDFRCC-60-56D. However, this analysis also evaluated the tendency to decline of the maximum load of R-HFDFRCC-40-56D compared to that of R-HFDFRCC-50-56D.

4.2. The effects of various material properties on the maximum load of R-HFDFRCC RC beam specimens

Based on IV A, above, we analyzed the effects of $F_c$, $G_Fc$, $F_{t,b}$, $\varepsilon_{tu,b}$, bond strength ($\tau_{max}$), and bond strength slip ($S_u$) on the maximum load of the R-HFDFRCC RC beam specimens. TABLE IV gives the analysis factors. In the analysis, taking the analysis of the loading test of R-HFDFRCC RC beam specimens (R-HFDFRCC-50-56D) as the reference criterion, we assumed as parameters $F_c$, $G_Fc$, $F_{t,b}$, $\varepsilon_{tu,b}$, $\tau_{max}$, and $S_u$. Additionally, the fluctuation ranges of the parameters were set with reference to the material properties of R-HFDFRCC with different W/B, as shown in TABLE II above.

| Specimen | Compression | Bending | Pull-out |
|----------|-------------|---------|----------|
|          | $F_c$ (N/mm$^2$) | $E$ (GPa) | $G_{Fc}$ (N/mm$^2$) | $F_{t,b}$ (N/mm$^2$) | $\varepsilon_{tu,b}$ | $\tau_{max}$ (N/mm$^2$) | $S_u$ (mm) |
| R-HFDFRCC-50-56D | 35.4 | 59.7 | 2.25 | 0.0302 | 15.8 | 0.357 |
| Case-1   | 20.0 | 55.0 | 2.00 | 0.0302 | 15.8 | 0.357 |
| Case-2   | 30.4 | 65.0 | 2.50 | 0.0302 | 15.8 | 0.357 |
| Case-3   | 35.4 | 59.7 | 2.25 | 0.0302 | 15.8 | 0.357 |
| Case-4   | 15.9 | 59.7 | 2.25 | 0.0302 | 15.8 | 0.357 |
| Case-5   | 10.0 | 59.7 | 2.25 | 0.0302 | 15.8 | 0.357 |
| Case-6   | 20.0 | 59.7 | 2.25 | 0.0302 | 15.8 | 0.357 |
| Case-7   | 0.0604 | 0.0604 | 0.0604 | 0.0604 | 0.0604 | 0.0604 |
| Case-8   | 0.200 | 0.200 | 0.200 | 0.200 | 0.200 | 0.200 |
| Case-9   | 0.500 | 0.500 | 0.500 | 0.500 | 0.500 | 0.500 |
| Case-10  | 15.8 | 0.357 | 0.357 | 0.357 | 0.357 | 0.357 |
| Case-11  | 15.8 | 0.357 | 0.357 | 0.357 | 0.357 | 0.357 |
| Case-12  | 15.8 | 0.357 | 0.357 | 0.357 | 0.357 | 0.357 |
| Case-13  | 15.8 | 0.357 | 0.357 | 0.357 | 0.357 | 0.357 |
| Case-14  | 15.8 | 0.357 | 0.357 | 0.357 | 0.357 | 0.357 |

Table 4. Analysis factors.
The relationships between the maximum loads obtained from the analyses and analytical parameters.

Fig. 9 shows the relationships between the maximum loads obtained from the analyses and analytical parameters.

According to Fig. 9 (a) (Case 1, R-HFDFRCC-50-56D and Case 2), when $F_c$ increased to 20.0 between 35.4 N/mm$^2$, the maximum load increased by 20.1 kN; when $F_c$ increased from 35.4 to 50.4 N/mm$^2$, the maximum load increased by 9.08 kN.

According to Fig. 9 (b), (c), and (f), when $G_{fc}$ is in the range between 55.0 to 65.0 N/mm, $\tau_{max}$ between 10.0 to 20.0 N/mm$^2$, and $S_u$ between 0.200 to 0.500 mm, the maximum load does not fluctuate significantly, regardless of the differences between $G_{fc}$, $\tau_{max}$, and $S_u$.

Next, according to Fig. 9 (c) (Case 5, R-HFDFRCC-50-56D and Case 6), when $F_{t,b}$ is in the range between 2.00 to 2.50 N/mm$^2$, the maximum load increases linearly with the increase in $F_{t,b}$. When $F_{t,b}$ increases from 2.00 to 2.50 N/mm$^2$, the maximum load increases by 16.4 kN.

According to the results in the event of Fig. 9 (d), where $F_c = 35.4$ N/mm$^2$ (Case 7, R-HFDFRCC-50-56D and Case 8), when $\varepsilon_{tu,b}$ increases from 0.0190 to 0.0302, the maximum load increases by 4.45 kN. According to the results when $F_c = 50.4$ N/mm$^2$ (Case 13, Case 2, and Case 14), when $\varepsilon_{tu,b}$ increased from 0.0190 to 0.0302, the maximum load increased by 6.86 kN. It is understood that the effects of $\varepsilon_{tu,b}$ on maximum load differs depending on the reference $F_c$. However, even if $\varepsilon_{tu,b}$ is magnified from 0.0302 to 0.0604, regardless of the difference in $F_c$, the maximum load hardly increases.

Based on the foregoing and within the scope of this study, the R-HFDFRCC material properties that have significant influence on the maximum loads of R-HFDFRCC RC beam specimens are $F_c$ and $F_{t,b}$. Additionally, the $\varepsilon_{tu,b}$ of R-HFDFRCC, within the range of 0.0190 to 0.0302, affects the maximum load of the R-HFDFRCC RC beam specimens.

In short, the fluctuations in the maximum load of the RC beam specimens in accordance with differences in W/B can generally be explained analytically as long as we understand the differences in the material properties (mainly compressive strength, tensile strength, and ultimate tensile strain) of R-HFDFRCC.

As further analysis with Young’s modulus ($E_o$) and Poisson’s ratio ($\nu$) as parameters, with the R-HFDFRCC RC beam specimen (R-HFDFRCC-50-56D) loading test serving as the reference criterion. When $E_o$ was increased from 15.9 to 19.3 kN/mm$^2$, we found the maximum load decreased by 1.30 kN; when $\nu$ increased from 0.207 to 0.229, the maximum load decreased by 2.58 kN, indicating that these values also affected maximum load to some degree.
5. Conclusion
We obtained the following findings within the scope of this study:
1) The maximum load of an R-HFDFRCC RC beam specimen with a water-binding ratio of 40% decreases compared to that with a water-binding ratio of 50%. Analysis confirmed this tendency.
2) When the water-binding ratio is 50%, the maximum load of an R-HFDFRCC RC beam specimen with shear reinforcement bars increased 73.4% compared to that of an R-HFDFRCC RC beam specimen without shear reinforcement bars.
3) The maximum load of an R-HFDFRCC RC beam specimen is affected within an R-HFDFRCC ultimate tensile strain range of 0.0190 to 0.0302.
4) The fluctuations in the maximum load of R-HFDFRCC RC beam specimens in accordance with differences in water-binding ratios can generally be explained as long as the differences in the material properties (mainly compressive strength, tensile strength, and ultimate tensile strain) of R-HFDFRCC are understood.

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