Tensile Properties of HDCC for Repairing Hydraulic Discharge Structures

Bo Chen\(^1\)*, Li-Ping Guo\(^2\), Zheng-Kai Chen\(^2\) and Cong Ding\(^2\)

\(^1\) State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing Hydraulic Research Institute, Nanjing 210029, P.R. China

\(^2\) School of Materials Science and Engineering, Southeast University, Nanjing 211189, P.R. China

* bchen@nhri.cn

Abstract. To develop high ductility cementitious composites (HDCC) for repairing hydraulic discharge structures, the effect of water-binder ratio, polyvinyl alcohol (PVA) fiber content, and fly ash content on the tensile properties of HDCC was studied. The results show that with increase in water-binder ratio and/or fly ash content, the ultimate tensile strain of HDCC increases gradually, while the ultimate tensile stress and the initial cracking stress decrease. With different fiber contents, the tensile stress-strain curves of HDCC coincide in the linear elastic stage, and the initial cracking stresses are roughly the same; with increase in fiber content, the ultimate tensile strain and ultimate tensile strength increase gradually. Based on these results, the appropriate mix proportions for the HDCC material were determined for repairing hydraulic discharge structures.

1. Introduction

Hydraulic discharge structures get severely damaged by the impact of bed load and the erosion of suspended load, so they need frequent repairs [1]. The repair work done to rectify the erosion damage to a hydraulic discharge structure directly affects the safe operation of the structure. Hence, much attention is being paid to this issue by the engineers and operators of the structures [2].

Organic materials such as epoxy and polyurea have advantages of high strength, high abrasion resistance, short curing time, etc [3]. However, the high thermal expansion coefficient (i.e., 2–3 times that of concrete) of the organic materials would cause uncoordinated thermal deformation between the organic repair layer and the concrete substrate. The construction technology that uses organic materials demands a high degree of drying of the damaged basement concrete. Therefore, defects such as hollowing and peeling can easily emerge in the organic repair layer; this can lead to premature failure of the repair material. With conventional cement-based materials\[^4\] such as high-strength concrete or high-strength mortar, premature deterioration of the repair layer often occurs because of shrinkage cracking and lack of cohesive force.

It is necessary to develop a new type of material for repair of hydraulic discharge structures. High ductility cementitious composite (HDCC) is a type of cement-based material whose thermal expansion coefficient is similar to that of concrete; it has excellent deformation compatibility and high interface bonding strength [5,6]. At the same time, HDCC can improve anti-abrasion ability, volume stability,
and long-term durability of the repair layer because HDCC has high impact resistance and excellent ductility [7,8].

In this work, the effect of water-binder ratio, PVA fiber content (by volume), and fly ash replacement level (by weight) on the tensile properties of HDCC was studied, and the appropriate mix proportions for the HDCC material were selected for the repairing of hydraulic discharge structures.

2. Materials, mix proportions, and test methods

2.1. Materials

The materials used in the production of HDCC mixtures were P-II 42.5R Portland cement (C), Grade I fly ash (FA) with a calcium content of 6.09%, river sand with a maximum grain size of 1.18 mm, ordinary tap water, PVA fibers, and a polycarboxylate type high-performance water-reducing admixture (HPWRA). The chemical component and physical properties of the Portland cement and fly ash are presented in Tables 1-3.

The PVA fibers with an equivalent diameter >40 μm and a length of 12 mm are specially manufactured with an ultimate tensile strength $\geq$1300 MPa, elastic modulus $>$35 GPa, and ultimate elongation in the range of 8–10%; these properties are required for achieving the required strain hardening performance. Additionally, the surface of the PVA fibers is specially treated to modify the interfacial properties between the fiber and matrix to achieve the strain hardening performance.

### Table 1. Chemical component of cement and fly ash (wt.)

| Chemical component | CaO | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | MgO | SO$_3$ | others |
|--------------------|-----|---------|-------------|-------------|-----|---------|---------|
| Cement (%)        | 60.60 | 21.84   | 7.32        | 3.70        | 1.77 | 2.24    | 2.53    |
| Fly ash (%)       | 6.09  | 49.96   | 33.02       | 4.52        | 1.17 | 0.62    | 4.62    |

### Table 2. Physical and mechanical properties of cement.

| Specific surface area (m$^2$/kg) | Water requirement of normal consistency (%) | Setting time (min) | Soundness | Flexural strength (MPa) | Compressive strength (MPa) |
|----------------------------------|---------------------------------------------|-------------------|-----------|------------------------|----------------------------|
|                                 |                                             | Initial | Final    | 3d | 28d | 3d | 28d |
| 370                             | 27                                           | 150     | 205      | Qualified              | 4.8                        | 8.0                        | 29.2                      | 48.5                      |

### Table 3. Physical properties of fly ash.

| Percent retained on 45μm (%) | Water requirement ratio (%) | loss on ignition (%) | Specific surface area (m$^2$/kg) | Density (kg/m$^3$) | Moisture content (%) | Strength activity index (%) |
|------------------------------|----------------------------|----------------------|----------------------------------|--------------------|----------------------|----------------------------|
| 4.6                          | 92                         | 3.1                  | 454                              | 2240               | 0.2                  | 73                         |

### Table 4. Mix proportions of HDCC (S/B = 0.30).

| Mix ID  | C (kg/m$^3$) | FA (kg/m$^3$) | Sand (kg/m$^3$) | Water (kg/m$^3$) | PVAF (kg/m$^3$) | HPWRA (kg/m$^3$) | W/B   | FA/Binder (%) | Vf (%) |
|---------|--------------|---------------|----------------|------------------|-----------------|------------------|-------|---------------|--------|
| 0.20-40-2% | 794          | 529           | 397            | 265              | 26              | 10               | 0.20  | 40            | 2.0    |
| 0.25-40-2% | 768          | 512           | 384            | 320              | 26              | 6                | 0.25  | 40            | 2.0    |
| 0.30-40-2% | 744          | 496           | 372            | 320              | 26              | 4                | 0.30  | 40            | 2.0    |
| 0.30-80-1% | 248          | 992           | 372            | 372              | 13              | 1                | 0.30  | 80            | 1.0    |
| 0.30-80-1.5% | 248         | 992           | 372            | 372              | 19.5            | 1                | 0.30  | 80            | 1.5    |
| 0.30-80-2% | 248          | 992           | 372            | 372              | 26              | 1                | 0.30  | 80            | 2.0    |
| 0.30-60-2% | 496          | 744           | 372            | 372              | 26              | 2                | 0.30  | 60            | 2.0    |
2.2. Mix proportions
To investigate the influence of water-binder ratio, PVA fiber content, and fly ash content on the tensile properties of HDCC, seven types of HDCC mixtures were designed. The mix proportions of the mixtures are presented in Table 4. The variable parameters in these mixtures were the water-binder ratio (W/B) (0.20, 0.25, and 0.30), PVA fiber content (V_f = 1.0%, 1.5%, and 2.0% by volume), and fly ash replacement level (FA/B = 40%, 60%, and 80% by mass). The mass ratio of sand to the total binder materials (binder = Portland cement + fly ash) of the mixture was held constant (S/B = 0.30 by mass). HPWRA was added to adjust the workability and flowability of the fresh HDCC material, and the HPWRA content was not kept constant.

For the meaning of mix id, an example is given. 0.3-40-2% means a water-binder ratio of 0.30, fly ash replacement level of 40% (by mass), and fiber content of 2.0% (by volume).

2.3. Test methods
Flexural strength and compressive strength tests: The mechanical properties were measured using 40 mm × 40 mm × 160 mm prism specimens at the age of 28 days according to "Method of testing cements- Determination of strength (ISO)" (GB/T 17671-1999).

Uniaxial tensile tests: According to the Japan Society of Civil Engineers code, “Recommendations for Design and Construction of High Performance Fiber Reinforced Cement Composites with Multiple Fine Cracks (HPF RCC)”, the tensile property was measured using dumbbell-shaped specimens with thickness of 13 mm, parallel portion width of 30 mm, parallel portion length of 100 mm, and original reference point distance of 100 mm. Uniaxial tensile tests were conducted using MTS 810 servo-hydraulic testing system in displacement control mode. The loading rate used was 0.3 mm/min. Aluminum plates were glued on both sides of the dumbbell-shaped specimens’ ends to facilitate gripping. Two external linear variable displacement transducers (LVDTs) were attached to the specimens with a gauge length of approximately 100 mm to measure the elongation of the specimens. Complete tensile stress-strain curves were recorded. In this study, the ultimate tensile strain of each HDCC specimen is defined as the strain at the softening point of the uniaxial tensile stress-strain curves, and the ultimate tensile stress is defined as the value of maximum stress obtained in the strain hardening region.

3. Results and Discussion
3.1. Mechanical properties
The test results of flexural strength and compressive strength are presented in Table 5. The standard deviation (SD) of flexural strength varies in the range of 0.1–0.6, and the SD of compressive strength varies in the range of 0.8–3.5. The maximum coefficient of variation (C.V.) of flexural strength and compressive strength are 6.4% and 4.0%, respectively. The values of SD and C.V. indicate that the test results on the HDCC specimens have the desired data variation.

With a fly ash replacement level of 40% and fiber content V_f = 2%, the water-binder ratio varies in the range of 0.20–0.30. The water-binder ratio is found to have a significant effect on the mechanical properties. With decrease in water-binder ratio, the flexural strength and compressive strength are found to increase steadily. Between flexural strength and water-binder ratio, the linear regression relationship y = 6x + 18.533 was obtained, and the correlation coefficient R^2 from the regression analysis was 0.871; between compressive strength and water-binder ratio, y = -230x + 133.07 and R^2 = 0.9994 were obtained.

With a water-binder ratio of 0.30 and fly ash replacement level of 80%, the fiber content varies in the range of 1%–2%. Between flexural strength and fiber content, the linear relationship y = 2.4x + 4.8667 and correlation coefficient R^2 = 0.871 were obtained. The compressive strength values were in the range of 39.5–41.9, with the difference between the maximum and minimum values being only 2.4; hence, the fiber content is found to have no significant effect on compressive strength.
Table 5. Mechanical properties of HDCC.

| Mix ID     | Flexural strength | Compressive strength |
|------------|-------------------|----------------------|
|            | Test value (MPa)  | Assessment value (MPa) | SD (MPa) | C.V. (%) | Test value (MPa)  | Assessment value (MPa) | SD (MPa) | C.V. (%) |
| 0.20-40-2% | 17.5              | 16.9                 | 17.7     | 17.4     | 3.5             | 86.9                  | 80.5      | 87.1     | 3.5           | 4.0 |
| 0.25-40-2% | 16.6              | 16.9                 | 17.3     | 16.9     | 2.4             | 76.8                  | 75.4      | 76.7     | 2.4           | 3.2 |
| 0.30-40-2% | 16.3              | 16.9                 | 17.2     | 16.8     | 0.8             | 64.5                  | 63.8      | 64.1     | 0.8           | 1.2 |
| 0.30-80-1% | 7.3               | 7.8                  | 7.1      | 7.4      | 1.3             | 40.5                  | 38.5      | 41.6     | 1.3           | 3.2 |
| 0.30-80-1.5% | 8.1           | 8.3                  | 8.1      | 8.2      | 3.6             | 40.3                  | 39.2      | 41.7     | 3.6           | 4.1 |
| 0.30-80-2% | 10.3              | 10.0                 | 9.1      | 9.8      | 1.7             | 42.9                  | 40.2      | 40.0     | 1.7           | 4.1 |
| 0.30-80-2% | 14.0              | 15.1                 | 14.9     | 14.7     | 1.8             | 43.8                  | 44.1      | 42.2     | 1.8           | 4.2 |

With a water-binder ratio of 0.30 and fiber content \( V_f = 2\% \), the fly ash replacement level varies in the range of 40%-80%. Between flexural strength and fly ash content, the linear relationship \( y = 0.175x + 24.67 \) and correlation coefficient \( R^2 = 0.9494 \) were obtained. For compressive strength, a nonlinear relationship was observed.

3.2. Uniaxial tensile properties

The effects of water-binder ratio, fiber content, and fly ash replacement level on the stress-strain relationship of HDCC are shown in Figures 1~3. The tensile test specimens of seven types of HDCC have significant characteristics of strain hardening and multiple fine cracks. The ultimate tensile strain is in the range of 1.4%-6.1%, and the ultimate tensile stress is in the range of 1.8 MPa–8.3 MPa.

For water-binder ratios of 0.20, 0.25, and 0.30, the ultimate tensile strains are 1.4%, 1.9%, and 2.5%, and the ultimate tensile stresses are 8.3 MPa, 6.1 MPa, and 5.2 MPa (see Figure 1). With increase in water-binder ratio, the ultimate tensile strain increases, and the ultimate tensile stress decreases gradually. For HDCC with water-binder ratios of 0.25 and 0.30, the ultimate tensile strain increased by 36% and 79%, respectively, and the ultimate tensile stress decreased by 37% for both ratios, with respect to the corresponding values for HDCC with a water-binder ratio of 0.20. The range of stress variation was lower than that in the case of strain.

The initial cracking stress and the range of strain variation rapidly decreased with increase in water-binder ratio. In the given range, the water-binder ratio is found to have a positive linear correlation with the ultimate tensile strain, and negative linear correlation with the ultimate tensile stress.

For PVA fiber contents of 1.0%, 1.5%, and 2.0%, the ultimate tensile strains are 2.5%, 3.6%, and 6.1%, and the ultimate tensile stresses are 1.8 MPa, 2.2 MPa, and 2.9 MPa (see Figure 2). With increase in PVA fiber content, both the ultimate tensile strain and ultimate tensile stress are found to increase.
Figure 1. Effect of water-binder ratio on stress and strain.

Figure 2. Effect of PVA fiber content on stress and strain.

Figure 3. Effect of fly ash content on stress and strain.

For HDCC with PVA fiber contents of 1.5% and 2.0%, the ultimate tensile strain increased by 44% and 144%, respectively, and the ultimate tensile stress increased by 22% and 61%, respectively, with respect to the corresponding values for HDCC with a PVA fiber content of 1.0%. The range of strain variation is significantly higher than that in the case of stress. With different PVA fiber contents, HDCC tensile strain curves overlap in the linear elasticity stage, and the initial cracking stresses are
also approximately the same. In the given range, the PVA fiber content has a positive linear correlation with the ultimate tensile strain and ultimate tensile stress.

For fly ash replacement levels of 40%, 60%, and 80%, the ultimate tensile strains are 2.5%, 4.4%, and 6.1%, respectively, and the ultimate tensile stresses are 5.2 MPa, 4.6 MPa, and 2.9 MPa, respectively (see Figure 3). With increase in fly ash replacement level, the ultimate tensile strain increases and the ultimate of tensile stress decreases gradually.

For HDCC with fly ash contents of 60% and 80%, the ultimate tensile strain increased by 76% and 144%, respectively, and the ultimate tensile stress decreased by 12% and 37%, respectively, with respect to the corresponding values for HDCC with a fly ash replacement level of 40%. The range of strain variation is significantly higher than that in the case of stress. With different fly ash contents, HDCC tensile strain curves coincide in the linear elasticity stage, and the initial cracking stress decreases with fly ash content. In the given range, the fly ash replacement level has a positive linear correlation with the ultimate tensile strain, and negative linear correlation with the ultimate tensile stress.

The grades of concrete for hydraulic discharge structures normally vary in the range of C40–C60, so compressive strength higher than 60 MPa is needed for the repair material. The ultimate tensile strain required is normally higher than 2% to achieve the required ductility [9]. Considering the demands on compressive strength and ductility, HDCC of the type 0.3-40-2% is appropriate for the application. The 28-day compressive strength of HDCC of the type 0.3-40-2% is 63.9 MPa, and the ultimate tensile strain is 2.5%.

4. Conclusions
(1) With increase in water-binder ratio and/or fly ash replacement level, the ultimate tensile strains of HDCC increases gradually, while the ultimate tensile stress and the initial cracking stress decrease.

(2) With different fiber contents, the tensile stress-strain curves of HDCC coincide in the linear elastic stage, and the initial cracking stresses are roughly the same. The PVA fiber content has a positive linear correlation with the ultimate tensile strain and ultimate tensile stress.

(3) HDCC with a water-binder ratio of 0.30, fly ash replacement level of 40%, and fiber content of 2% is appropriate for repairing hydraulic discharge structures.

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References
[1] Müller H S, Bohner E, Vogel M, et al. 2013 Procedia Engineering 54 22
[2] Ojha B K 2015 Water and Energy International 58 53
[3] Wang X, Luo S, Liu G, et al. 2014 Water Science and Engineering 7 106
[4] Roy M, Ray I, Davalos J F 2013 Journal of Materials in Civil Engineering 26 04014074
[5] Guo L P, Chen B, Sun W, et al. 2018 Journal of Building Structures 39 169
[6] Kunieda M 2006 Journal of Advanced Concrete Technology 4 19
[7] Guo L P, Chen B, Sun W, et al., Journal of the Chinese Ceramic Society 44 1609
[8] Mechtcherine V 2013 Construction and Building Materials 41 365
[9] Li M, Li V C 2011 ACI Materials Journal 108 3