Study on the relationship between tensile strength and three-dimensional total area of cement-based materials

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Study on the relationship between tensile strength and three-dimensional total area of cement-based materials

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Abstract. In this paper, the three-dimensional fracture surface of cement paste with different systems was reconstructed by KEYENCE ultra-depth-of-field three-dimensional micro-system. The three-dimensional effective area of fracture surface was calculated based on calculus principle. Combined with fracture load, the effective cracking stress of different cement paste was calculated. The three-dimensional total area and tensile strength are fitted and regressed according to polynomial function, linear function, logarithmic function, power function and exponential function. The results show that the polynomial function can accurately describe the relationship between the three-dimensional total area and tensile strength...

1. Introduction
Describing the various geometric characteristics of fracture surfaces in a quantitative manner has been a very active field in recent years. In order to reveal the role of various structures and external factors in the fracture process, it provides a good means to establish some relations between the geometrical characteristics of fracture surface and material properties [1,2]. But the analysis so far is limited to the relatively easy two-dimensional analysis. From the anisotropy of fracture itself and other influencing factors [3], it is not comprehensive to estimate the extremely complex three-dimensional fracture morphology only according to the two-dimensional parameters of a certain section [4, 5].

Based on this, the three-dimensional fracture surface of cement paste with different systems was reconstructed by KEYENCE ultra-depth-of-field three-dimensional micro-system, and the three-dimensional effective area of fracture surface was calculated. Combined with tensile strength, the effective cracking stress of different cement paste was calculated. The three-dimensional total area and tensile strength are fitted and regressed according to polynomial function, linear function, logarithmic function, power function and exponential function, and compared and analyzed. The three-dimensional reconstruction of complex fracture surface and the direct measurement of geometric parameters and the relationship between them are discussed.

2. Test
2.1. Materials
The cement used in the study was type I/II Portland cement with fineness 381 m²/kg. 28d flexural strength of the samples was 7.5MPa. Fly ash (FA) with apparent density of 2.2 g/cm³ was used, and it is a low-calcium ash with fineness 454 m²/kg. The fineness of silica fume (SF) was about 20000 m²/kg. Ground blast furnace slag (GBFS) with fineness of 740 m²/kg and apparent density of 2.88 g/cm³ was used.
2.2. Test mixture ratio
Controlling the water cement ratio of the cement slurry to be 0.3 and 0.35 respectively; The mixed materials are fly ash, ground slag and silica fume respectively, and the content of the mixed materials is 15 %, 25 % and 5 % of the total amount of the cementing materials respectively. The mix design is shown in table 1.

| Series | Mix        | W/B | C(g) | W(g) | FA(g) | GBFS(g) | SF(g) |
|--------|------------|-----|------|------|-------|---------|-------|
| A1     | Control    | 0.3 | 2600 | 780  | 0     | 0       | 0     |
| A2     | Control    | 0.35| 2600 | 910  | 0     | 0       | 0     |
| B1     | 15% FA     | 0.3 | 2210 | 780  | 390   | 0       | 0     |
| B2     | 15% FA     | 0.35| 2210 | 910  | 390   | 0       | 0     |
| C1     | 25%GBFS    | 0.3 | 1950 | 780  | 0     | 650     | 0     |
| C2     | 25%GBFS    | 0.35| 1950 | 910  | 0     | 650     | 0     |
| D1     | 5% SF      | 0.3 | 2470 | 780  | 0     | 0       | 130   |
| D2     | 5% SF      | 0.35| 2470 | 910  | 0     | 0       | 130   |

2.3. Test methods
The specimen is 40x40x160 mm, after being demoulded the specimens are put into water for curing to test age, the curing temperature is (20±2)℃. Then the following tests are carried out: firstly, the tensile strength of each group of test pieces is measured, and the average value is taken; Protect section well, using KEYENCE super depth of field three-dimensional micro system to shape the fracture surface of each specimen three-dimensional morphology, and through the mathematical method to calculate the effective cross-sectional area of fracture surface of tensile fracture specimen, finally combined with tensile strength to calculate the effective cracking stress of different cement paste was broken, the three-dimensional total area and tensile strength according to polynomial function, linear function, logarithmic function, power function and exponential function fitting regression analysis, comparative analysis. The KEYENCE ultra-depth-of-field three-dimensional microscopic system is as shown in figure 1.

Figure 1. KEYENCE ultra-depth three-dimensional microscopy system

3. Test results and analysis

3.1. The tensile strength of each group of specimens is shown in table 2.

| Specimen number | A1 | A2 | B1 | B2 | C1 | C2 | D1 | D2 |
|-----------------|----|----|----|----|----|----|----|----|
| Tensile strength(Mpa) | 3.6| 3.2| 2.53| 2.48| 2.84| 2.65| 2.3| 2.2|
3.2. Three-dimensional morphology of fracture surface of remolded specimen

The actual morphology of the fracture surface of the C1 sample is shown in figure 2. The three-dimensional morphology of the fracture surface of the specimen was modeled by KEYENCE, as shown in figure 3. Because the use of this instrument has the requirement of depth of field range, the overall section area of the test is relatively large, and the surface of the concave and convex condition is relatively small, so the observation will be a specimen section is divided into four parts, each part of the measured area is the effective section area of the cross section. Figure 4 shows a processed three-dimensional sectional perspective view.

![Figure 2. The actual morphology of fracture surfaces of C1 sample](image1)

![Figure 3. The stereoscopic pattern of the four sections of C1](image2)

![Figure 4. The three-dimensional map in crack section with elevation](image3)

3.3. Calculation of three-dimensional effective cross-sectional area of tensile test piece

Due to the requirements of the depth of field of the test instrument, and in order to improve the test accuracy, each 40 mm x 40 mm interface is divided into eight partitions as shown in Fig. 5, the plane
area of each partition is 10 mm x 10 mm = 100 mm. Ten elevation difference curves are measured from top to bottom in each partition, and the length of any curve is calculated by using Fortran language and principle of calculus. Assuming that the width of each curve is 1 mm, the three-dimensional effective fracture area of this part is $A_1 = s \times 1 \text{ mm} \times 10$, and the three-dimensional effective area of section $a1$ is $A = A_1 + A_2 + \ldots + A_8$.

Table 3. Effective cross-sectional area of $A_1$

| Name of each part | Area per partition (mm$^2$) | Three - dimensional total area (mm$^2$) | Total area of plane (mm$^2$) |
|-------------------|----------------------------|----------------------------------------|----------------------------|
| 1                 | 368.381                    |                                        |                            |
| 2                 | 347.838                    |                                        |                            |
| 3                 | 314.061                    |                                        |                            |
| 4                 | 225.863                    | 2541.644                               | 800                       |
| 5                 | 218.479                    |                                        |                            |
| 6                 | 493.138                    |                                        |                            |
| 7                 | 246.195                    |                                        |                            |
| 8                 | 327.688                    |                                        |                            |

Table 4. Effective cross-sectional area

| Specimen number | Tensile strength (Mpa) | Three - dimensional total area (mm$^2$) | Cracking stress density (Mpa/ mm$^2$) |
|-----------------|------------------------|----------------------------------------|-------------------------------------|
| A1              | 3.6                    | 2541.644                               | 1.42E-03                            |
| A1              | 3.2                    | 2202.400                               | 1.45E-03                            |
| B1              | 2.53                   | 2123.390                               | 1.19E-03                            |
| B2              | 2.48                   | 2230.400                               | 1.11E-03                            |
| C1              | 2.84                   | 2073.750                               | 1.37E-03                            |
| C2              | 2.65                   | 2000.000                               | 1.33E-03                            |
| D1              | 2.3                    | 2858.610                               | 8.05E-04                            |
| D2              | 2.2                    | 3004.800                               | 7.32E-04                            |

3.4. Analysis of the relationship between the three-dimensions total area and tensile strength

According to polynomial function, linear function, logarithmic function, power function and exponential function, the tensile strength and the total area of fracture surface were fitted and regressed respectively, and the results are compared and analyzed.
Figure 6. The polynomial function relationship between three-dimensional areas and tensile strength

\[
y = -3070x^3 + 27261x^2 - 80234x + 80367
\]

\[R^2 = 0.9698\]

Figure 7. The linear function relationship between three-dimensional areas and tensile strength

\[
y = -782.36x + 4392.8
\]

\[R^2 = 0.646\]

Figure 8. The logarithmic function relationship between three-dimensional areas and tensile strength

\[
y = -2289.5\ln(x) + 4527.6
\]

\[R^2 = 0.6845\]

Figure 9. The power function relationship between three-dimensional areas and tensile strength

\[
y = 6122.6x^{-1.0242}
\]

\[R^2 = 0.7173\]
Figure 10. The exponential function relationship between three-dimensional areas and tensile strength

4. Conclusions

1) The three-dimensional morphology of fracture surfaces of different specimens can be formed by using KEYENCE ultra-depth-of-field three-dimensional micro-system; The three-dimensional effective area of tensile fracture specimen section can be calculated by mathematical method, and combined with tensile strength, the effective cracking stress of different cement pastes can be calculated.

2) Analysis and fitting regression the relationship between the three-dimensional total area and tensile strength by polynomial function, linear function, logarithmic function, power function and exponential function, it can be found that the polynomial function fitting effect is the best, its correlation coefficient is the largest.

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