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# Effect of Water-Cement Ratio on Brittleness Characteristics of Concrete under Uniaxial Compression

**Shanchao Hu**

*China Coal Technology Engineering Group Chongqing Research Institute, Chongqing 400037, China*

***Corresponding Author:** ***Shanchao Hu,*** *China Coal Technology Engineering Group Chongqing Research Institute, Chongqing 400037, China.*

**Abstract:** *In order to explore the influence of water-cement ratio change on the ductility of concrete under uniaxial compression. First, uniaxial compression tests were performed on six concrete samples with different water-cement ratios (P = 0.50, 0.53, 0.56, 0.59, 0.62, and 0.65) to obtain the stress-strain curves of concrete under different water-cement ratios. Second, concrete was used. Ductility formula, combining the four parameters of peak stress, residual stress, peak strain, and residual strain of concrete with different water-cement ratios, to obtain the relationship between the concrete's stress drop, brittleness coefficient and water-cement ratio, and finally the fracture of the concrete after failure Electron microscopy was performed to obtain its micromorphology. The results show that as the water-cement ratio increases, the uniaxial compressive strength of the concrete decreases, and the peak strain and residual strain increase; the relative rate and brittleness of the concrete's post-peak stress drop and post-peak stress drop with the water-cement ratio. As the water-cement ratio increases, the distribution of fragile features decreases, while the number and size of the dimples gradually increase, and the tendency of the dimples to communicate with each other strengthens. The evolution of ductility and micro-morphological characteristics indicates that the higher the water-cement ratio, the lower the brittleness of concrete.*

**Keywords:** *water-cement ratio; stress-strain curve; brittleness; microscopic morphology*

## 1. INTRODUCTION

As a kind of composite material, concrete plays an important role in underground geotechnical engineering such as mine grouting and support. At present, when it is subjected to external loads, the research mainly focuses on the influence of the ratio on the peak strength [1-2], Poisson 's ratio [3], permeability [4] and other physical and mechanical parameters of concrete. Chang et al. [4] made four kinds of high-porosity concrete with different proportions. After uniaxial compression of concrete, it was found that the peak strength of concrete decreased with the increase of water-cement ratio. Wu et al. [5] found that the flexural strength of rubber concrete increased with the decrease of water cement ratio. Song Hui et al [6] found that the permeability coefficient of pervious concrete decreases with the increase of water-cement ratio. A series of studies have found that the change of the ratio has an important influence on the mechanical properties of concrete [7].

As one of the important mechanical properties of concrete, the ductility of concrete can significantly affect the stability of concrete, and the stability is a key index to evaluate the application life of concrete in engineering. In the uniaxial compression test, the commonly used definition methods of brittleness ductility index mainly include brittleness index based on strength characteristics [8-10], brittleness index based on full stress-strain curve [11-12], brittleness index based on hardness [13-15], brittleness index based on internal friction angle [16] and energy method [17-18]. Wang Xuebin et al. [19] found that the brittleness decreased after the peak, and the precursor of rock failure became obvious. By defining the brittleness index of rock strength attenuation coefficient, Peng et al. [20 ] found that the coefficient has a power function relationship with confining pressure in triaxial test. In the past, most of the research on brittle ductility focused on rock, and in the study of concrete, it often focused on the mechanical properties and energy dissipation of concrete, while the effect of ratio change on the ductility of concrete, especially water-cement ratio, was less [21].Therefore, taking the water-cement ratio as a prominent factor, it is of great significance to study the brittleness and ductility of concrete under uniaxial compression for studying the durability of concrete in engineering applications.

In order to study the influence of water-cement ratio on the ductility of concrete, six kinds of concrete with different water-cement ratios ( P = 0.50,0.53,0.56,0.59,0.62, and 0.65 ) were prepared in this paper. Through uniaxial compression tests on different water-cement ratios, the ductility of concrete with different ratios was analyzed based on the post-peak stage of stress-strain curve. At the same time, combined with the micro-morphology of the fragments after concrete failure, the influence of the change of ratio on the ductility of concrete was studied. The research results have important engineering application significance.

## 2. Test Equipment and Test Methods

### 2.1. Preparation of the Sample

The cement in this test is P•O 32.5 ordinary Portland cement produced by Xuzhou Zhonglian Cement Plant. The chemical composition of the cement is shown in Table 1. The II grade fly ash, admixture and hydrogen peroxide foaming agent produced by Tongshan Coal-fired Power Plant are composed. The water-cement ratio P = 0.50, 0.53, 0.56, 0.59, 0.62, and 0.65 was prepared. The pattern making process and maintenance were based on the concrete production standards. The concrete after mixing is shown in Fig. 1, and finally made into a cube concrete pattern with a size of 100 mm × 100 mm × 100 mm.

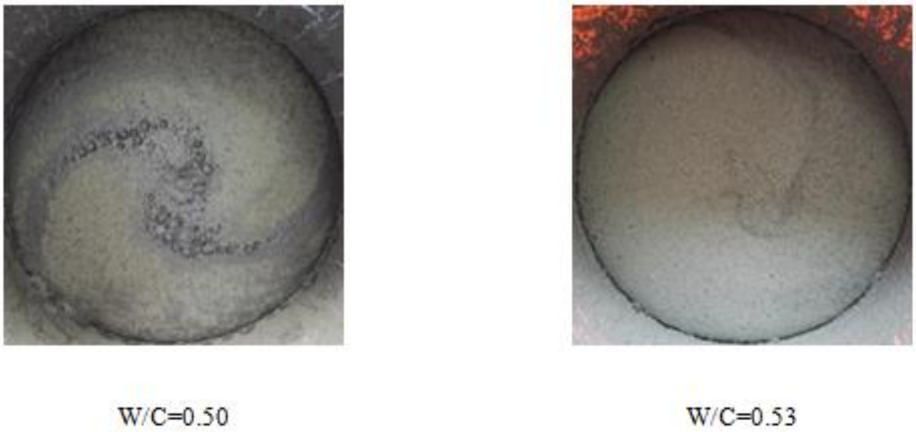



**Fig1.** *Schematic diagram of foaming effect of foamed cement*

**Table1.** *Chemical composition of cement and fly ash*

| $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $Na_2O$ | $K_2O$ | $SO_3$ | ignition loss |
|---|---|---|---|---|---|---|---|---|
| 21.6% | 4.13% | 4.57% | 64.44% | 1.06% | 0.11% | 0.56% | 1.74% | 0.76% |

### 2.2. Test Apparatus and Method

Test equipment: The impact load test uses the Hopkinson experimental system of the State Key Laboratory of Deep Geotechnical Mechanics and Underground Engineering of China University of Mining and Technology. The system consists of a control system, a dynamic loading system, and a data acquisition system. The data acquisition is the displacement-load acquisition system carried by the test loading equipment itself; the main test instruments are shown in Fig.1.

Test process: During the test, the horizontal and vertical strain gauges are first attached to the side of the sample, and then the sample with the strain gauge is placed on the universal testing machine, and the displacement loading method is used to load at a loading speed of 0.002mm / s until the macroscopic failure of the sample occurs.

**Fig2.** *Test instrument diagram*

## 3. THE INFLUENCE OF WATER CEMENT RATIO ON THE DUCTILITY OF CONCRETE

### 3.1. The Influence of Water Cement Ratio on the Physical and Mechanical Properties of Concrete

Figure 3 is the stress-strain curve of concrete with different water-cement ratio. From Figure 3, it can be seen that the influence of water-cement ratio change on the physical and mechanical properties of concrete is mainly reflected in the following aspects : the stress corresponding to different strains is different, which is mainly reflected in the rise slope of the approximate linear elastic stage in the full stress-strain curve of concrete decreases with the increase of water-cement ratio ; the decrease of peak strength indicates that the bearing capacity of concrete decreases with the increase of water cement ratio. The peak strain εd and residual strain εp increase with the increase of water cement ratio.

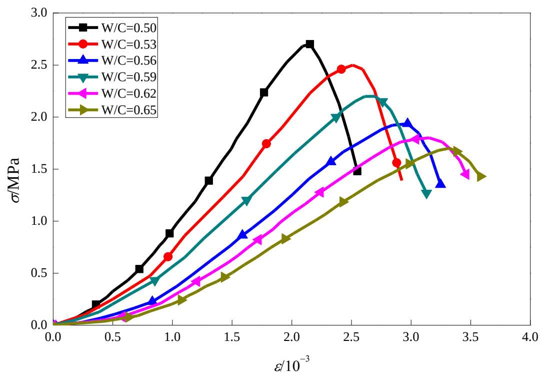



**Fig3.** *Stress-strain curves of concrete with different water-cement ratios*

Fig.4 shows the variation curve of concrete strain with water cement ratio. It can be seen from Figure 3 that the influence of the change of water-cement ratio on the strain of concrete is mainly reflected in the following : the peak strain εd of concrete increases gradually with the increase of water-cement ratio. When the water-cement ratio is 0.5, the peak strain εd of concrete is the smallest, which is 2.15. When the water-cement ratio increases to 0.65, the peak strain εd of concrete increases to 3.32, which is 54.24 % higher than the peak strain when the water-cement ratio is 0.5. The peak strain εd increases approximately linearly with the change of water-cement ratio, indicating that the increase of water-cement ratio reduces the anti-deformation ability of concrete. The residual strain εp of concrete increases gradually with the increase of water-cement ratio. When the water-cement ratio is 0.5, the residual strain εp of concrete is the smallest, which is 2.55. When the water-cement ratio increases to 0.65, the peak strain εd of concrete increases to 3.58, which is 40.39 % higher than the peak strain when the water-cement ratio is 0.5. The residual strain εp increases approximately linearly with the change of water-cement ratio.

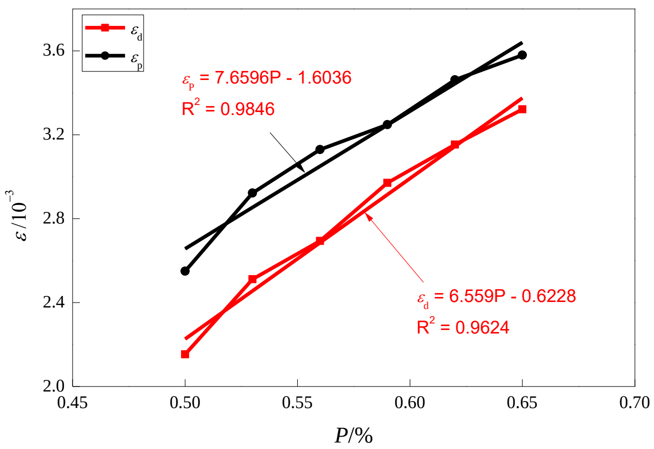



**Fig4.** *The strain curve of concrete with water cement ratio*

### 3.2. Ductility Calculation Principle of Concrete

The stress-strain curve of concrete can reflect the relationship between stress and deformation. By studying the shape of the post-peak stress-strain curve of concrete, the brittleness of concrete can be understood [ 10, 11 ]. A large number of studies have shown that the post-peak stress drop can reflect the ductility change of concrete to a certain extent. The expression of stress drop is as follows [ 22-23 ] :

$$\alpha = \frac{\sigma_d - \sigma_p}{\sigma_d} \tag{1}$$

In the formula, $\alpha$ is the stress drop, $\sigma_d$ is the peak stress, and $\sigma_p$ is the residual stress.

The stress drop can be used to reflect the magnitude of the stress change after the peak to a certain extent, but the simple use of stress drop to express brittleness has certain limitations. For example, in the case of the same stress drop, due to the different rate of stress-strain curve decline in the post-peak stage, the brittleness of concrete is not necessarily the same, so the relative rate of stress-strain curve decline in the post-peak stage of concrete must be considered. Since the range of stress drop is 0-1, in order to make the data representation more intuitive, the relative rate of stress drop is divided by 10, so that the range of relative rate is 0-1. The expression of the relative rate is as follows [23 ]:

$$\beta = \frac{\lg\left|\frac{\sigma_d - \sigma_p}{\varepsilon_d - \varepsilon_p}\right|}{10} \tag{2}$$

In the formula, $\beta$ is the relative rate of stress drop, and its geometric meaning indicates that the peak strength of concrete reaches the residual strength connection rate.

Finally, combining Eq. (1) and Eq. (2), the degree of brittleness and ductility of concrete is expressed as follows [23]:

$$\lambda = \alpha\beta = \frac{\sigma_d - \sigma_p}{\sigma_d} * \frac{\lg\left|\frac{\sigma_d - \sigma_p}{\varepsilon_d - \varepsilon_p}\right|}{10} \tag{3}$$

In the formula, $\lambda$ is the degree of brittle ductility. In formula (3), because the range of stress drop and its relative rate is 0-1, the range of brittle ductility degree $\lambda$ is also 0-1. For the brittleness of the material corresponding to the value of the brittle ductility degree $\lambda$, the related research shows that the greater the stress drop is, the stronger the brittleness is, the greater the relative rate of stress drop after the same peak is, the stronger the brittleness is. Therefore, the closer the value of the brittle ductility degree $\lambda$ is to 1, the weaker the ductility of the material is, and the closer to 0, the stronger the ductility of the material is.

### 3.3. The Change Rule of Concrete Ductility with Water Cement Ratio

Using the formulas (1), (2) and (3) combined with the full stress-strain curves of concrete with different water-cement ratios, the stress drop, post-peak relative slope and ductility of concrete can be calculated.

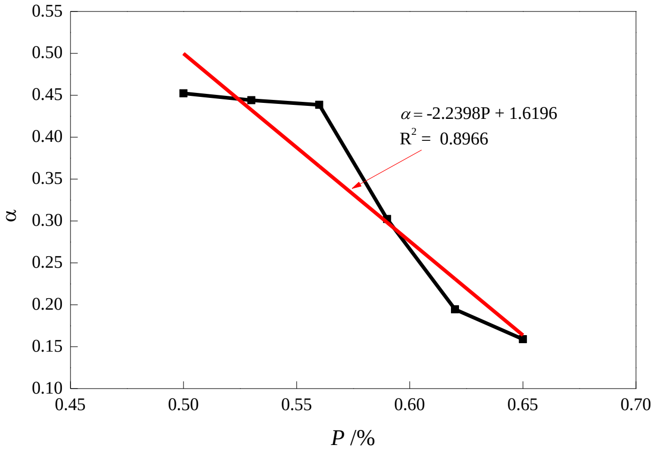



**Fig5.** *The variation of stress drop of concrete with water cement ratio*

Fig.5 shows the variation of stress drop of concrete with water cement ratio. From Figure 5, it can be seen that the water-cement ratio has a significant effect on the stress drop of concrete, which is mainly manifested in the approximate linear decrease of the stress drop of concrete with the increase of water-cement ratio. When the water-cement ratio is 0.5, the corresponding stress drop is 0.452. When the water-cement ratio increases to 0.65, the corresponding stress drop is 0.159, which is 64.89 % lower than the stress drop when the water-cement ratio is 0.5. The change of stress drop reflects the ductility of concrete to a certain extent with the increase of water-cement ratio [13].

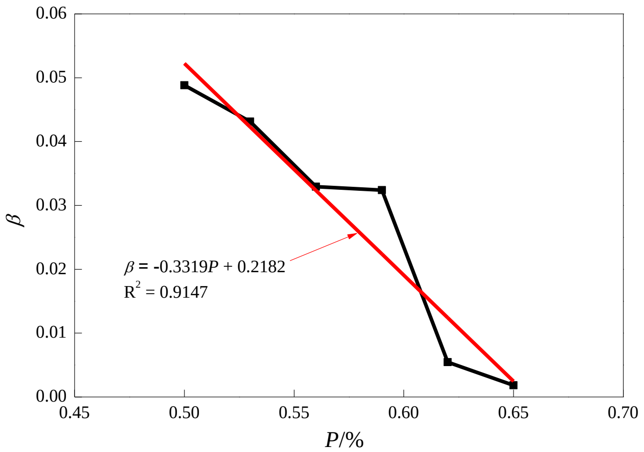



**Fig6.** *Variation of relative slope of post-peak stress drop of concrete with water-cement ratio*

Fig.6 shows the variation of the relative slope of the stress drop after the peak of the concrete with the water-cement ratio. It can be seen from Fig.6 that the water-cement ratio has a significant effect on the relative slope of the stress drop of the concrete, which is mainly reflected in the fact that the relative slope of the stress drop of the concrete decreases approximately linearly with the increase of the water-cement ratio. When the water-cement ratio is 0.5, the corresponding relative slope is 0.0488. When the water-cement ratio increases to 0.65, the corresponding relative slope is 0.0018, which is 96.24 % lower than the relative slope when the water-cement ratio is 0.5.

Fig.7 shows the variation of brittleness coefficient of concrete with water-cement ratio. It can be seen from Figure 7 that the water-cement ratio has a significant effect on the ductility of concrete, which is mainly manifested in the approximate linear decrease of the brittleness of concrete with the increase of water-cement ratio. When the water-cement ratio is 0.5, the corresponding brittleness is 0.0221.When the water-cement ratio increases to 0.65, the corresponding brittleness is 0.0003, which is 98.68 % lower than that when the water-cement ratio is 0.5. From the brittleness of concrete with water-cement ratio, it shows that the increase of water-cement ratio increases the ductility of concrete and reduces its brittleness.

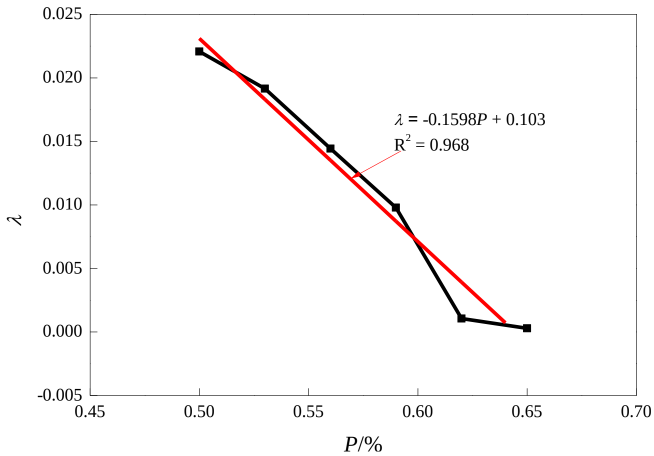



**Fig7.** *The variation of brittleness of concrete with water-cement ratio*

## 4. THE EFFECT OF WATER CEMENT RATIO ON THE MICROSTRUCTURE OF CONCRETE

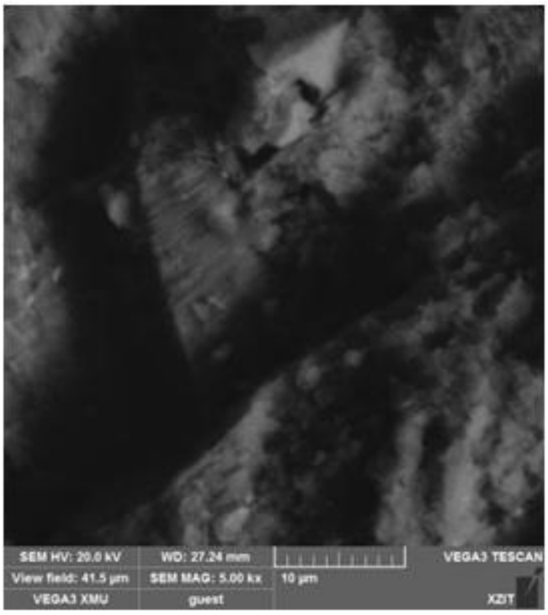
In order to better study the influence of the change of water-cement ratio in concrete on its brittleness and ductility under uniaxial compression, the damaged concrete fragments were subjected to electron microscope scanning test, and its microscopic morphology reflected the change of its macroscopic performance to a certain extent [24-25].

### 4.1. Test Equipment and Pattern Preparation

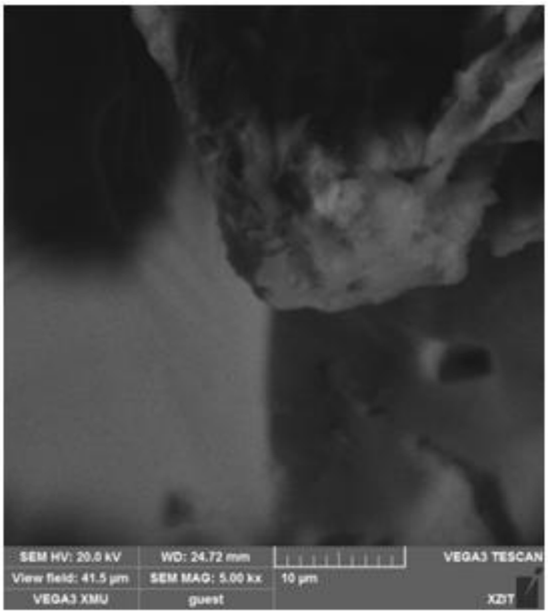
Test equipment: This test equipment adopts the scanning electron microscope (SEM) system (VGEA3) introduced by Xuzhou Institute of Technology.

The sample preparation process: Firstly, the smooth plane of the concrete fracture section after uniaxial compression is taken as the observation surface, and the fragments on the observation surface are taken as the observed body. The diameter of the fragments is about 1.5 cm; secondly, the surface of the fragment is gently brushed with a brush until there is no visible dust on the surface of the fragment. Then, the fragments were put into the drying oven for 24 hours, and the dried fragments were sprayed with gold powder in the SBC-12 small example sputtering instrument. Finally, the fragments sprayed with gold powder were put into a scanning electron microscope.

### 4.2. Micro-Morphological Characteristics of Concrete under Different Water-Cement Ratios




$P$=0.5




$P$=0.53

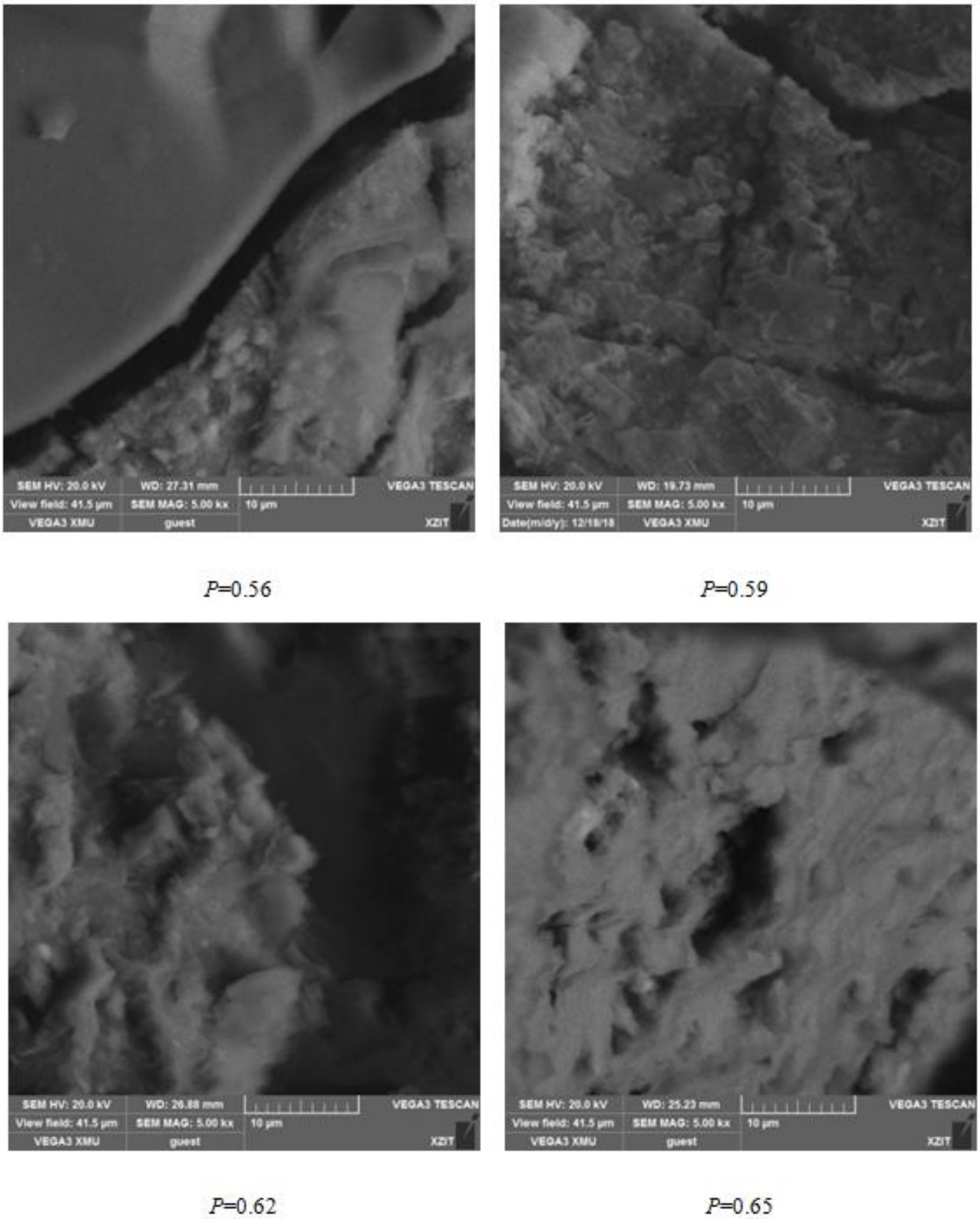



**Fig8.** *Microscopic morphology of concrete fragments with different water-cement ratios after uniaxial compression*

Fig. 8 is the micro-morphology of concrete with different water-cement ratios. It can be seen from Fig.8 that when P = 0.5, a certain amount of dimples appear on the observation surface, and there are step patterns in addition to dimples. When P = 0.53, a certain amount of scattered dimples appear on the observation surface, and there is a fog-like slip zone. In addition, there are river patterns with brittle characteristics. When P = 0.56, a certain amount of dimples appear on the observation surface. The size of the dimples is small and independent of each other. In addition to the dimples, there are step patterns. When P =0.59, the observation surface is loose and a large number of dimples are distributed, and a small number of dimples are interconnected; when P = 0.62, a large number of dimples appear. The size of the dimples is larger than that of the water-cement ratio of 0.59, and some of the dimples are connected with each other. When P = 0.65, a large number of large-sized dimples appear in the whole observation surface, and most of the dimples are interconnected.

With the increase of water-cement ratio, the brittleness characteristic patterns of concrete gradually decrease, while the number of ductility characteristic patterns increases, the size increases and the trend of mutual penetration increases, indicating that the brittleness of concrete gradually decreases with the increase of water-cement ratio, and the ductility gradually increases [24]. The microscopic change law is consistent with the brittleness coefficient law obtained from the strain curve.

## 5. Conclusion

In order to explore the influence of water-cement ratio on the brittleness of concrete, this paper first conducts uniaxial compression tests on concrete under six different ratios. Secondly, the ductility of concrete is calculated by using the brittleness function combined with the stress-strain curve of concrete under different water-cement ratios, and the relationship between brittleness and water-cement ratio is obtained. Finally, the microstructure of concrete with different water-cement ratios was observed by scanning electron microscopy of the fragments after the test. The following conclusions are obtained:

1) With the increase of water-cement ratio, the peak strength of concrete decreases gradually, and the peak strain and residual strain increase gradually.
2) With the increase of water-cement ratio, the post-peak stress drop, the relative slope of stress drop and the ductility coefficient of concrete gradually decrease, and show an approximately linear decrease relationship with water-cement ratio.
3) With the increase of water-cement ratio, the distribution of brittle characteristic patterns decreases, the number and size of dimples increase gradually, and the trend of interpenetration between dimples is strengthened. The variation of brittle characteristic pattern and dimple distribution with water-cement ratio shows that the brittleness of concrete decreases with water-cement ratio.

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