Effect of Water Content on Tensile Properties of Cement Mortar

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Abstract. In order to study the effect of water content on the tensile properties of cement mortar, the “8” test method was used for the five water contents of the two mix ratios (saturation was 0%, 25%, 50%, 75%, and 100% respectively.) A total of 100 cement mortar specimens were subjected to a uniaxial tensile test. The test results show that the stress-strain curves of the cement mortar specimens are similar under different saturation, and the stress increases nonlinearly with the increase of the strain. After the peak strain is reached, the specimens are destroyed. The curve has no yield stage and shows the characteristics of brittle materials of the cement mortar; As the saturation increases, the tensile strength, peak strain and fracture toughness of the cement mortar specimens first decreased and then increased, and showed a linear relationship; the cement with a saturation of 50% mortar specimens have the lowest tensile properties. Compared with cement mortar samples with saturation of 0%, the tensile strength, peak strain, and fracture toughness were reduced by 40%, 24%, and 50%, respectively; the peak strain of cement mortar specimens with 100% saturation was the largest. The cement mortar specimens with a saturation of 0% increase by 24%; by comparing the tensile properties of cement mortar specimens at two different mix ratios (water-cement ratios of 0.55 and 0.45, respectively), it was found that the water-cement ratio was not the same. The effect of saturation on the tensile properties of cement mortar is similar, verifying the accuracy of the test results.

1. Introduction

With the widespread use of concrete in underwater structures, issues of durability are getting common. For example, the concrete failed to achieve the expected strength leading to the building construction; the deformation of the concrete beyond the critical value make the building structure unable to work properly, and etc. Based on the above problems, Wang Hailong et al.[1,2] studied the effect of water environment on the mechanical properties of concrete. The results show that the mechanical properties of concrete decrease as the water content inside the concrete increases. This is because concrete is a kind of porous brittle material, and there are microscopic cracks and pores in the interior. Under the influence of the external water pressure and the surface tension of the liquid, the free water will enter the pores or cracks of the concrete structure, causing the water content of the concrete to increase, and thus forming a saturated concrete. The free water in the internal pores will have a certain effect on the pore wall under the influence of external loads, which will affect the mechanical properties of the concrete [3]. The destruction of concrete occurs first in the micro-cracks in the cement mortar. With the increase of the load, the micro-cracks continue to expand and penetrate each other, leading to concrete damage.
Therefore, it is of great significance to study the effect of water content on the mechanical properties of cement mortar.

With regard to the effect of water content on the mechanical properties of cement mortar, domestic and foreign scholars have conducted a large number of experimental studies and have obtained a lot of research results. Among them, Rossi[4] proposed that water content is one of the main factors affecting the material rate effect; Ding Ning et al.[5] studied the effect of water content on the compressive performance of cement mortar, and the results showed that the compressive strength of cement mortar would decrease as the water volume increases. Logunova[6] concludes that the dynamic compressive strength of wet concrete specimens is higher than that of dry concrete specimens by comparing the compressive strength of concrete specimens in dry and wet conditions; Wang Tao et al. [7] studied the influence of moisture content on the compressive strength of mortar. The results showed that the compressive strength of cement mortar showed a decreasing trend when the moisture content increased, and the formula of cement mortar considering the influence of moisture content was put forward by comparing the experimental results with existing theories. Most of the above scholars have studied the effect of water content on the compressive performance of cement mortar, however, there are few studies on the effect of water content on the tensile properties of cement mortar which are lack of necessary research data and experimental data. And the tensile performance is an important performance index of cement mortar. It is one of the standards to measure structural safety in engineering construction. Therefore, it has broad application prospects to study the effect of water content on the tensile properties of cement mortar.

Based on this, the uniaxial tensile test of cement mortar specimens with a water/cement ratio of 0.55 was carried out using the “8” test method. By analyzing the stress-strain curve, tensile strength, peak strain, and the relationship between toughness and saturation, the effect of different water content on the tensile properties of cement mortar was studied. In addition, a cement mortar specimen with a water/cement ratio of 0.45 was added as a supplementary test. The relationship between tensile strength and water content of cement mortar under two kinds of water/cement ratio was compared which can verify the accuracy of the test results.

2. Test

2.1. Test materials and mix ratio
The cement adopts PꞏO 42.5 ordinary Portland cement produced by Xi'an Venus Cement Plant, and its performance indicators are in line with ordinary Portland cement standards. The sand is ordinary river sand with a specific gravity of 2.49 and a bulk density of 1580 Kg/m³. The used water was laboratory tap water, of which the quality met the testing standards, and no water-reducing agent was added in the mortar preparation.

In order to test the accuracy of the conclusions, the MS1 and MS2 mortar mix ratios were designed and compared. The detailed cement mortar mix design is shown in Table 1.

| Tab. 1 Mortar mix ratio /Kg·m-3 | Water cement ratio |
|----------------------------------|-------------------|
| Group               | Cement | Water | Sand |               |
| MS1                 | 335    | 609.1 | 1218.2 | 0.55          |
| MS2                 | 291.9  | 648.6 | 1297.2 | 0.45          |

2.2. Preparation of test pieces
According to the mixing ratio in Table 1, the material is poured into the mixer in the order of sand-water-cement, and poured uniformly after being stirred, and then the mortar is loaded into the “8” shape of the pre-painted release agent with a cement mortar knife. In the mould, the pestles were inserted
evenly, then the surface was made sure to be smooth, and finally is was put on the vibration table of the mortar to make a compaction; after demolishing it for 1d, demoulding and numbering was carried out, then the specimen was put in water for curing for 7 days, the temperature should be 20±2 °C; Under certain test conditions (temperature should be 20±2 °C, relative humidity 95%) curing 21d. 50 test pieces were prepared for each mix ratio.

2.3. Determination of Cement Mortar Saturation
The moisture content of the cement mortar is measured by the saturation, and the saturation calculation formula [8] is shown in (1):

\[ S_r = \frac{W - W_d}{W_w - W_d} \]  

(1)

In the formula:
- \( S_r \) - the saturation of a test piece, %;
- \( W \) - the quality of the test piece, g;
- \( W_w \) - the mass of the specimen when the saturation is 100%, g;
- \( W_d \) - the mass of the specimen when the saturation is 0%, g.

In this test, the test piece was placed in a drying oven for drying. The temperature of the drying oven was set at 105 °C. For the cement mortar material, the time required for complete drying of the sample in the drying oven was 7 days at 105 °C. When the mass of the specimen is continuously weighed many times without change, the saturation of the specimen is considered to be 0%. Samples with a saturation of 0% were wrapped with plastic film to prevent the specimen from getting wet. Take out the specimen with saturation of 0% and soak it in water. When the mass of the specimen is continuously weighed many times and no change occurs, the specimen saturation is considered to be 100%. According to the formula of \( m = (W_w - W_d) / 2 \), the required water quality needed when saturation changed from 0% to 50% was calculated. Then the specimen was soaked into water with required amount. The specimen was weighed when the water is totally absorbed by the specimen. If the quality is constant after numerous weighing, it is considered that the sample saturation is 50%. According to a similar method, cement mortar specimens with saturation of 25% and 75% were prepared. The number of cement mortar samples corresponding to each saturation is 10 pieces.

2.4. Test methods
The “8” test method is used in this test, which refers to the tensile strength test method for epoxy mortars. By improving the shortcomings of small cross-sectional area, easy stress concentration, and large discrete test data, the proposed method can accurately reflect the tensile strength of cement mortar. Some scholars [9,10] compared this method with the existing test methods, and found that the “8” pattern method is not only easy to operate and high in work efficiency, but also has small fluctuations in test data and true measured tensile strength.

The test was divided into ten groups of ten test pieces, and the tensile strengths of cement mortar specimens with different water saturation ratios and five different saturation degrees were tested. Test tensile machine was H-S3001B electronic tensile testing machine, as shown in Figure 1. The test procedure is as follows:

1. Accurately place the "8"-shaped jig in the test position, and then put the mortar specimen symmetrically into the center of the jig along the stretching direction.

2. After installing the fixed extensometer, start the tester to load the test piece so that the jig is separated at a rate of (5±1) mm/min until the test piece is broken. Record the force-displacement curve during the failure process of the test piece and destroy the test piece. As shown in Figure 2 and 3.

3. Convert the force-displacement curve into a stress-strain curve, record the peak stress and peak strain at the time of failure of the test piece, and determine the fracture toughness of the test piece.
3. test results and analysis

3.1. The effect of saturation on the stress-strain curve of cement mortar

The stress-strain curve of cement mortar is an important figure describing its mechanical properties. The shape of the curve reflects the brittle deformation process of cement mortar under external force. Fig 4 shows the tensile stress-strain curves of cement mortar specimens at different saturation levels. As can be seen from the figure, under different saturation, with the increase of strain, the stress of the cement mortar specimens gradually increases; at different saturation, the stress-strain curves of cement mortar specimens have no yield stage. When the ultimate strain is reached, the specimen is destroyed and exhibits brittle material characteristics. Under the same strain, the stress of the cement mortar specimen gradually decreases with the increase of saturation, and the stress reduction amplitude increases with the strain.; cement mortar specimens with a saturation of 50% occurred at the earliest and the peak strain and peak stress were minimal.

| Type | Saturability /% | Strength of extension /MPa | Peak strain | Toughness /J m⁻³ |
|------|----------------|---------------------------|-------------|------------------|
| M1   | 0              | 3.76                      | 0.037       | 0.060            |
| M2   | 25             | 3.08                      | 0.036       | 0.045            |
### 3.2. Effect of Saturation on Tensile Strength of Cement Mortar

The tensile strength of cement mortar is the maximum stress value of cement mortar before breaking, and it also represents the fracture resistance of cement mortar. Fig 5 shows the tensile strength curves of cement mortar specimens at different saturation levels. From Table 2 and Fig 5, it can be seen that the tensile strength of the cement mortar specimen decreases first and then increases with the increase of saturation; the lowest tensile strength of the cement mortar specimen with a saturation of 50% is 2.28 MPa, which decreased by 40% and 16%, respectively when compared with the cement mortar with saturation of 0% and 100%. It can be seen that with the increase of saturation, the tensile strength of cement mortar specimen decreases more greatly than the increase; Both the descending and rising sections of the intensity curve are approximately straight lines with slopes of 0.03 and 0.009, respectively. It shows that the change of saturation has a significant effect on the tensile strength of cement mortar specimens.

| M3 | M4 | M5 |
|----|----|----|
| 50 | 75 | 100|
| 2.28 | 2.5 | 2.73|
| 0.033 | 0.04 | 0.046|
| 0.029 | 0.036 | 0.041|

### 3.3. Effect of Saturation on Peak Strain of Cement Mortar

The peak strain of cement mortar is an indicator to characterize the deformability of cement mortar and is an important measure for the safety analysis of engineering buildings. Fig 6 shows the peak strain curves of cement mortar specimens at different saturation levels. It can be seen from Table 2 and Fig 6 that with the increase of saturation, the peak strain curve of the cement mortar specimen first decreases and then increases, and the decrease is smaller than the increase; the saturation is 100%. The peak strain of the cement mortar specimen is the highest, which is 24% higher than that of the cement mortar specimen with a saturation of 0%; when the saturation is 25%, a slight mutation occurs in the falling portion of the curve, and the cement mortar test can still be considered. The peak strain of the piece changes linearly with increasing saturation.
3.4. Effect of Saturation on the Toughness of Cement Mortar
Fracture toughness, which indicates the ability of a material to absorb energy during the fracture process, is a measure of the material's ability to prevent macro crack propagation, and it is also a toughness parameter for a material to resist brittle failure. The better the toughness, the less likely the brittle fracture will occur\cite{11,12}. Fig 7 shows the fracture toughness curves of cement mortar specimens at different saturation levels. It can be seen from Table 2 and Fig. 7 that the fracture toughness of the cement mortar specimen first decreases and then increases with the increase of saturation, and the minimum toughness of the cement mortar specimen with a saturation of 50% is 0.029 J·m$^{-3}$. Compared with the cement mortar samples with saturation of 0% and 100%, respectively, it reduced by 50% and 30%; the saturation toughness of cement mortar specimens with different saturations is 0.060 J·m$^{-3}$, and the toughness is smaller. It shows that the cement mortar is a brittle material; however, the toughness varies within the range of 0.029-0.060 J·m$^{-3}$, and the fluctuation is large. Therefore, it can be considered that the change of saturation has a significant effect on the fracture toughness of the cement mortar specimen.

3.5. Mechanism Analysis
The tensile strength of cement mortar is closely related to its free water content\textsuperscript{[13]}. When the water content is 50%, under the quasi-static strain rate loading, due to the slow development of cracks inside the cement mortar, free water has enough time to reach the top of the crack. Under the action of external loads, the wedge force generated by free water will accelerate the development of cracks; In addition, the presence of water in the cracks will reduce the cohesion between the cement particles, so that the external force required for the cracks to develop is reduced, so as the water content increases, the tensile
The deformation behavior of mortar under tension is related to the deformation characteristics of C-S-H gel. The hydration product of cement mortar is mainly C-S-H, and its deformation characteristics directly affect the deformation performance of cement mortar. The CSH gel is a sandwich structure. With the increase of the water content of the fully-dried cement mortar, the free water breaks the sandwich structure of the CSH and forms a new double or multi-layer molecular structure, resulting in a decrease in the ability of the mortar to deform. With the increase of water volume, the peak strain of cement mortar gradually decreases. However, when the water content increases to 100%, the internal cracks of the cement mortar are completely filled with free water. The free water forms a water film on the inner wall of the crack. The water film completely fills the crack space, and the stability is improved. Therefore, the deformation amount is increased.

4. Comparison Test

Figures 8a to 8e respectively show the stress-strain curves, tensile strength, peak strain and fracture toughness with increasing saturation of cement mortar samples under two kinds of water-cement ratios. From Figs 8a and 8b, it can be seen that under different water-cement ratios, the stress-strain curves of the cement mortar specimens are all single-peak curves, and the development rules are similar. As the strain increases, the stresses all increase nonlinearly, and the stress growth rate increases gradually. When the peak stress is reached, the specimens are destroyed; there is no obvious straight line in the curve, no yield stage, and all exhibit brittle material characteristics; as the saturation increases, the stress strain of cement mortar specimens with different water-cement ratios gradually decreases with the slope of the curve. From figures 8c to 8e, it can be seen that the peak strain, tensile strength, and toughness curves of cement mortar specimens show a decreasing and then increasing characteristic with increasing water saturation ratio.

Both the segment and the descending segment are approximately linear, and the tensile properties and saturation of cement mortar specimens are linearly changed; the cement mortar specimens with a saturation of 50% have the lowest tensile properties; indicating that the water content is different from cement when the water-cement ratio is different. The effect of mortar's tensile properties is similar, which verifies the accuracy of the test results.
Fig. 8  Stress-strain curve, tensile strength, peak strain and toughness of cement mortar samples.

5. Conclusions
In this paper, the uniaxial tensile tests of cement mortar specimens with five different water contents (saturation levels of 0%, 25%, 50%, 75%, and 100%, respectively) were performed using the “8” pattern method. Tensile stress-strain curve, tensile strength, peak strain and toughness of the part were comprehensively analyzed in terms of the effect of saturation change on the tensile properties of the cement mortar, and a cement mortar specimen with a water-cement ratio of 0.45 was set up. Comparative tests ensure the accuracy of the test conclusions. The test results are as follows:

(1) Under different saturation, the stress-strain curves of the cement mortar specimens are similar, and the stress increases nonlinearly with the increase of the strain. After the peak strain is reached, the specimens are destroyed. The curve has no yield stage and shows the material characteristics of brittleness of the cement mortar;

(2) With the increase of the saturation, the tensile strength, peak strain and fracture toughness of the cement mortar specimen all show the characteristics of first decrease and then increase, and show a linear relationship;

(3) The cement mortar specimen with a saturation of 50% has the lowest tensile properties. Compared with cement mortar samples with saturation of 0%, tensile strength, peak strain and fracture toughness were reduced by 40%, 24%, and 50% respectively;

(4) The peak strain of the cement mortar specimen with the saturation of 100% is the largest, which is increased by 24% compared with the cement mortar specimen with the saturation of 0%;
5) Under different water-cement ratios, the effect of saturation changes on the tensile properties of cement mortar specimens is similar, which verifies the accuracy of the test results.

References

[1] Wang Hailong, Li Qingbin. Mechanism of free water in cracks under confining pressure affecting mechanical properties of concrete [J]. Journal of Tsinghua University, 2007, 47(9): 1443-1446.
[2] Li Qingbin, Wang Hailong. Review on the Effect of Water Environment on the Mechanical Properties of Concrete [J]. Sci China's Science and Technology Online, 2006, 1(2): 83-93.
[3] Deng Yousheng, Yan Weiling. Research progress on the effect of environmental water on the static strength of concrete[J]. Advances in Science & Technology of Water Resources, 2015, 35(4): 99-103.
[4] ROSSI P.A. physical phenomenon which can explain the mechanical behavior of concrete under high stain rates[J]. Materials and Structures, 1991, 24(6): 422-424.
[5] Ding Ning, Jin Long, Zhang Jian. Effect of Free Water Content on Dynamic Mechanical Properties of Cement Mortar at High Strain Rate[J]. Concrete, 2014(10): 128-142.
[6] LOGUNOVA V A. Dynamic strength of concrete[J]. Power Technology and Engineering, 1994, 28(6): 313-316.
[7] Wang Tao. Experimental Study on Influence of Moisture Content on Mortar Compressive Strength and Shear Strength of Brick Masonry [D]. Beijing: Dissertation of Beijing Jiaotong University, 2010.
[8] Du Xiuli, Wang Yang. Static and dynamic stress-strain relationship of cement mortar materials[J]. China Civil Engineering Journal, 2010(43): 119-126.
[9] Gong Xiaojian, Yang Yibo. Experimental Study on a New Method for Testing the Tensile Bonding Strength of Ready-mixed Cement Mortar[J]. Concrete, 2012(1): 100-102.
[10] Ouyang Xiang, Yang Yibo. On-site inspection technology of bond strength and compressive strength of ready-mix mortar [D]. Guangzhou, South China University of Technology, 2012.
[11] Liu Fangli, Yang Xiaojie. Effect of Fiber Parameters on Fracture Toughness of Cement Mortar[J]. Concrete & Cement Products, 2006(1): 40-43.
[12] Zhu Fangzhi, Liu Jian. Discussion on Influencing Factors of Moisture Content in Dynamic Modulus Testing[J]. Concrete, 2012(11): 41-56.
[13] Liu Bowen, Peng Gang, Qiu Sanbing. Experimental Study on Dynamic Behavior of Concrete Subjected to Cyclic Pore Water[J]. Civil Engineering and Environment Engineering, 2015, 37(5): 88-94.