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To cite this article: Guangfeng Wu *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **237** 032083

IOP Conf. Series: Earth and Environmental Science **237** (2019) 032083 doi:10.1088/1755-1315/237/3/032083

Experimental Study on Damage and Fracture Evolution Characteristics of Rock Material

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Abstract. The cement mortar specimens were used to simulate rock materials for uniaxial compression test and measurement of wave velocity during the test. Test results show that: The initial crack strengths of the specimens range from7.41 to 8.89MPa, with an average value of 8.32MPa; the value of uniaxial compressive strength ranges from 13.44 to14.93MPa with an average value of 14.14MPa. Overall view, the initial cracking strength of specimens fluctuates in a smaller range, but the uniaxial compressive strength is more discrete. The results of the wave velocity measurement show that: Before the surface of the specimen is cracked, the wave velocity of each measuring point has no obvious change with the increase of the load; when the specimen surface is cracked, the wave velocity of each the measured point decreased significantly with the increase of the load; after reaching the peak intensity, the wave velocity of each measuring point obviously decreased. From the obtained strain and wave velocity, the wave velocity and strain curve are plotted. The curve shows that each measurement point has a similar wave velocity-strain relationship diagram, the initial wave velocity values of measurement points 1#, 2#, and 3# are relatively close, and the initial wave velocity values of measurement points 5#, 6#, and 7# are relatively close to each other. The initial wave velocity value at 4# is in the middle of the initial wave velocity values at other measurement points, which is due to the uneven density distribution of the test piece.

1. Introduction

Rock is a component or material of the crust that has certain mineral composition and certain structural and structural characteristics under certain conditions of formation. Because of its high strength and small deformation, rock is widely used as engineering materials in road, tunnel and underground space. The damage of rock is mainly caused by the formation and development of the initial micro cracks. When the damage reaches a certain limit, macro-fractures will occur in the rock material, eventually destroying and causing great harm to people's lives. Most of the early foreign studies on damage of rock materials focused on how to establish damage constitutive models, such as works reported by Dougill et al[1,2], Mazars[3], Kachanov et al [4]. Brace and Bombolakis[5], Hoek et al[6] show that under the action of compressive stress, the extension of a single microcrack existing in the material is not the reason of macroscopic fracture instability, but it is caused by the convergence of microcracks, grain boundaries and voids. Xie Heping linked the microscopic damage of rock with the macroscopic fracture, quantitatively expounded the damage path of rock-like materials, and put forward the theory of damage fractal [7]. Hu Liuqing systematically studied the mechanism of rock

IOP Conf. Series: Earth and Environmental Science **237** (2019) 032083 doi:10.1088/1755-1315/237/3/032083

breakage under impact load, and analyzed the dynamic response relationship of rock fracture process from micro, meso and macro levels[8]. Zhang Ping et al combined the microscopic damage characteristics of rock materials with the macroscopic mechanical characteristics to established the theoretical formula for progressive damage localization model of fractured rock materials[9]. Yuan Xiaoping et al established a meso-mechanical model for microcrack propagation of rock. The damage and plastic properties of rock were studied. The damage and macroscopic plastic characteristics of the model were analyzed from factors, such as confining pressure and short microcrack length[10]. In recent years, as an important nondestructive testing technology, ultrasonic has the advantages of strong penetration, simple equipment, good use conditions and safety, wide range of detection. It has been an important means to study the damage and fracture mechanism of rock materials. Brich found that there was a linear positive correlation between the velocity of the longitudinal wave and the density of the rock[11]. Walsh et al.'s experimental results show that the velocity of ultrasonic wave in rock increases with the increase of load, but decreases with the increase of load during the process of compaction[12]. Shi Jinjin et al carried out impact damage experiments using rock sample, and obtained the relationship between rock impact damage characteristics and the change rate of sound wave velocity[13]. Li Xianglong et al studied the relationship between damage and wave length and amplitude of stress wave in rock materials through the effect of stress wave parameters on damage and failure of rock materials[14]. The acoustic emission and ultrasonic wave velocities of rock subjected to uniaxial compression damage were measured synchronously by Tiancheng et al. The variation of acoustic emission and wave velocity with damage process was compared and analyzed. At present, the research on damage constitutive relationship and fracture mechanism of rock materials has been mature, but there is less research on the evolution mechanism of rock materials from damage to fracture. In view of this, by using the cement mortar specimen to simulate rock material, the variation of wave velocity inside the specimen is measured by ultrasonic instrument and the variation law of wave velocity with load is analyzed through uniaxial compression test. Revealing the mechanism of damage-fracture evolution of rock materials provides a substantial supplement for the study of the extension theory of rock materials from microscopic damage to macroscopic fracture and provides a scientific basis for engineering application.

2. Preparation of test equipment and specimen

The uniaxial compression test of fractured rock was carried out using RMT-301 multifunctional electro-hydraulic servo testing machine, which developed by Wuhan Institute of Geotechnical Mechanics, Chinese Academy of Sciences. Displacement control was used to observe the variation of fracture and record it with a camera during compression. The DJUS-05 non-metallic ultrasonic instrument is used to measure the wave velocity in the single axis test, and the change of the wave velocity with the crack propagation is recorded to meet the needs of the test application and the basic theory research.

The specimens are made of ordinary Portland cement. The strength is 42.5 MPA, the mixture ratio of cement, river sand and water is 1: 3: 0.72. The length, width and height of the test specimens are 150mm, 150mm and 150mm, respectively. The test was carried out after molding and curing to the specified age of 28 days. A grid line is drawn on the symmetrical surface of the specimen to facilitate the alignment of ultrasonic measurement points. Seven ultrasonic measuring points are arranged on the symmetric surface respectively. The L1-L7# is the transmitting point and the receiving point are R1 #-R7#, as shown inFigure1 and Figure 2.

IOP Conf. Series: Earth and Environmental Science **237** (2019) 032083 doi:10.1088/1755-1315/237/3/032083

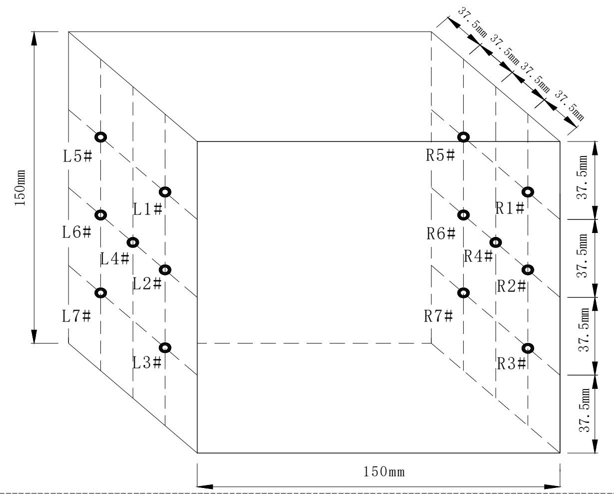


Figure 1. Three dimensional map of ultrasonic measurement points (Black spots show measuring point)

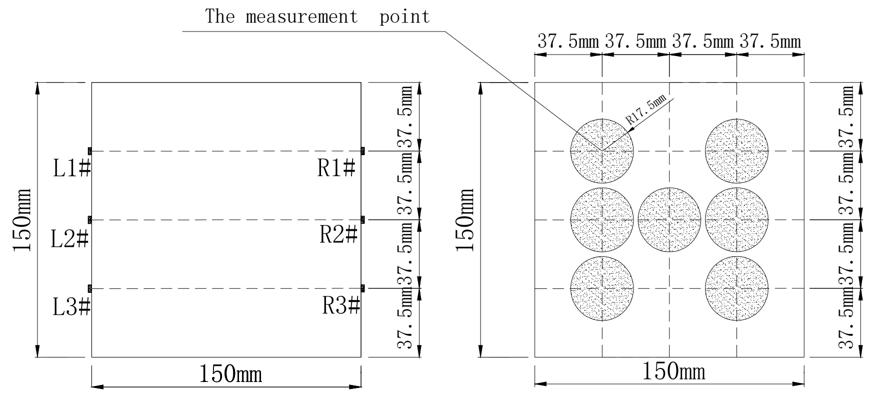


Figure 2. Layout plan of ultrasonic measurement points

3. Collation and analysis of test results

The uniaxial compression test was carried out on the testing machine. The specimens were divided into 15 groups, numbered WZ-1~15.The displacement is controlled with a moderate displacement rate of 0.002mm/s. The load is applied step by step, and the incremental load is 1.5MPa per stage, and the load is loaded until the specimen is destroyed. When loaded into each stage of load, the ultrasonic instrument is used to collect the wave velocity of each measuring point, as shown in figure 3.

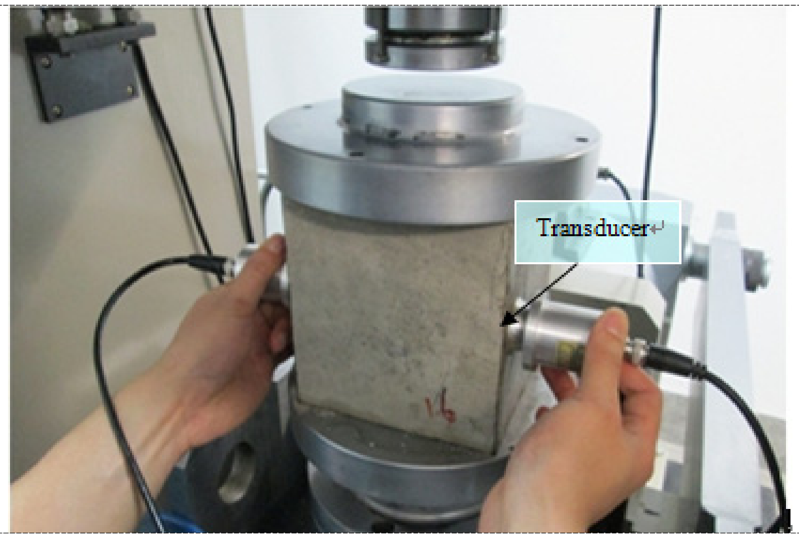
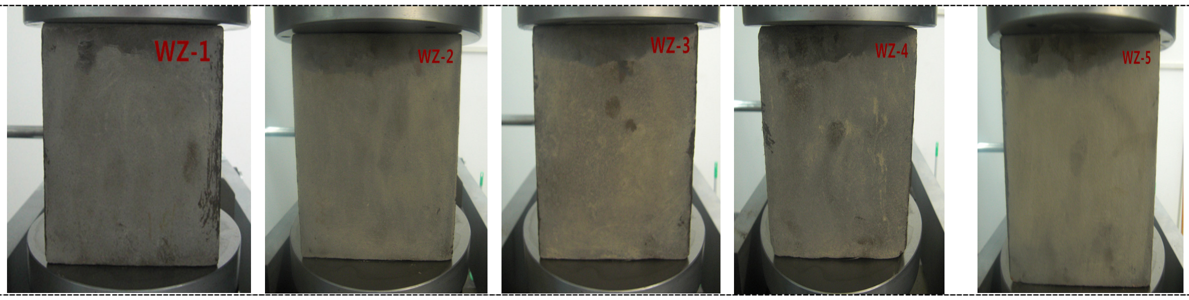


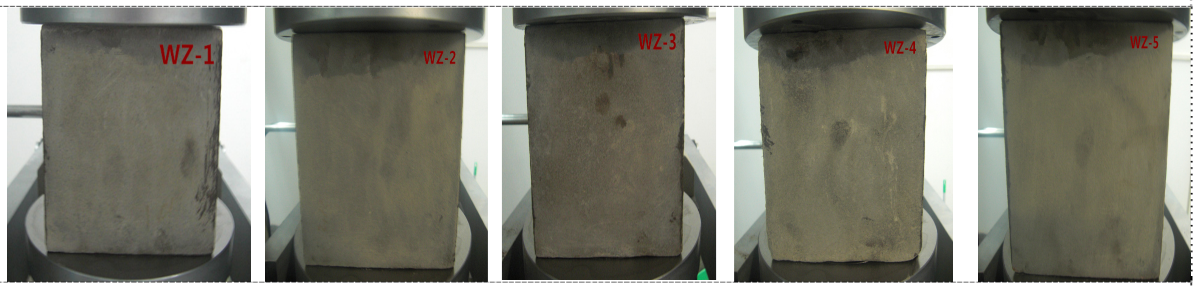
Figure 3. The picture of ultrasonic wave velocity

All specimens are made from the same composition, the same mix ratio, the curing period and the manufacturing method. Under the same test method, the variation of ultrasonic wave velocity in each specimen is the same, that is, the wave velocity of ultrasonic wave will decrease and the penetration ability of wave in the defect region will be greatly weakened when the defect is encountered. Due to the large number of test pieces (15 pieces), only the test results of 5 random samples are shown in Figure 4～9.



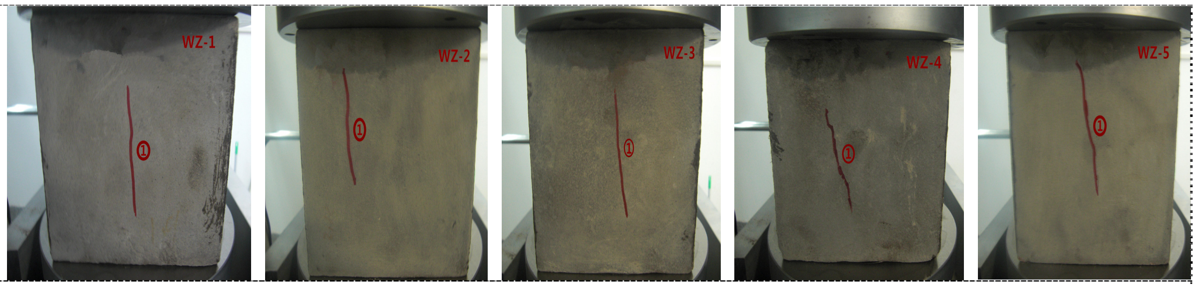
(a) (b) (c) (e) (f)

Figure 4. The picture of the specimen loads applied to 0MPa



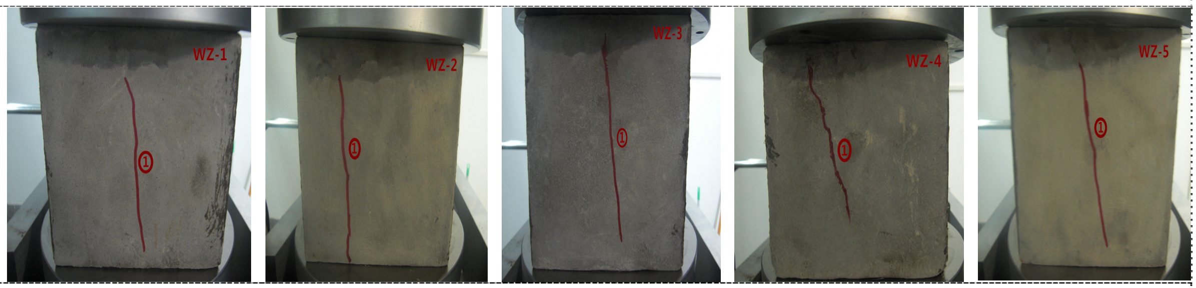
(a) (b) (c) (e) (f)

Figure 5. The picture of the specimen loads applied to 1.5-6MPa



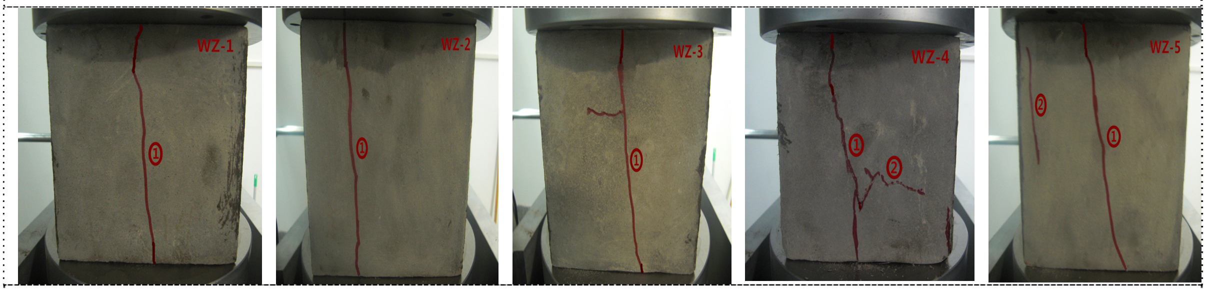
（a） （b） （c） （e） （f）

Figure 6. The picture of the specimen surface cracks



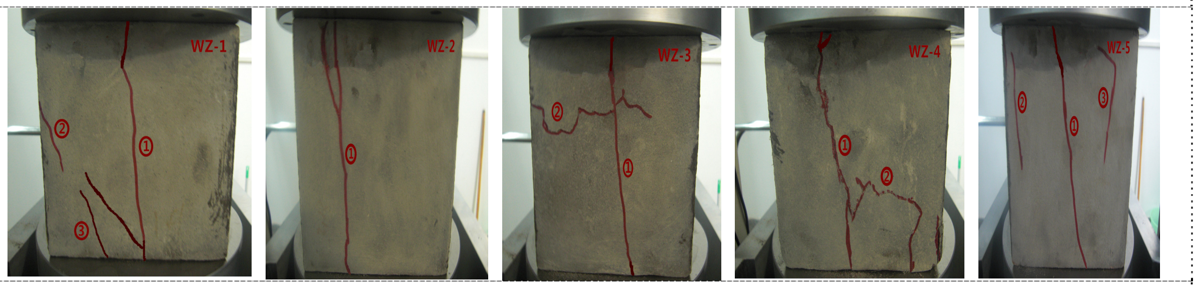
（a） （b） （c） （e） （f）

Figure 7. The picture of cracks starts to expand the picture



（a） （b） （c） （e） （f）

Figure 8. The picture of reaching the peak intensity



（a） （b） （c） （e） （f）

Figure 9. The picture of the specimen damage

From Figure 4～9, It can be seen that the damage-fracture evolution characteristics of specimens during compression can be divided into six stages:

(1) Internal damage stage: when the load is applied to 0MPa, defects such as air bubbles, micro-fissures, and micro-holes are already present during the fabrication and forming process of the specimen, and the micro-damage zone is formed inside the specimen (see Figure 4).

IOP Conf. Series: Earth and Environmental Science **237** (2019) 032083 doi:10.1088/1755-1315/237/3/032083

(2) Elastic damage stage: when the load is applied to 1.5-6MPa, no propagating track of precast crack is observed on the surface of the specimen. The stress of the whole specimen is in a linear elastic stage, and the damage can be recovered during unloading (see figure 5).

(3) Stage of damage manifestation: when the load continues to be applied, local cracks begin to appear on the surface of the specimen, indicating that the microcracks inside the specimen extend to the surface of the specimen to form macroscopic cracks (see figure 6). The strength at this point is recorded as the initial strength(that is, the strength value recorded when the specimen indicates a crack). The local crack length of WZ-1~5 specimen is 71.47 mm , 80.48 mm, 74.42 mm and 90.18 mm respectively, and the initial strength is 8.83 MPA / 7.59 MPA, 7.59 MPA and 8.88 MPA respectively.

(4) The damage expansion phase: the local crack on the surface extends gradually with the load increase, and the micro crack in the patch is irreversibly deformed, but it does not extend to the whole specimen, and the specimen can also bear large loads (see Figure 7). The local crack propagation lengths of WZ-1~5 specimens are: 110.38 mm, 125.01 mm, 125.12 mm, 107.65 mm and 119.73 mm, respectively. Compared with the present stage of damage, the crack propagation rate is 39.86% , 74.91% , 44.65% and 32.77% respectively.

(5) In the stage of the peak strength: the macroscopic crack expands continuously with the load continues to be applied and will gradually penetrate along a weakest path (the main crack), the main crack ① of each specimen extends to the bottom, the transverse direction of the crack becomes wider obviously. The extension lengths of the main crack ① of the WZ-1~5 specimen are 152.95mm, 150.07mm, 155.17mm , 152.20mm and 156.84mm respectively. Compared with the cumulative stage, the extension rates are 38.57% , 20.05% , 30.99mm respectively. And some of the specimens (WZ-3,WZ-4 and WZ-5) have branch cracks, which indicate that the whole specimen reached the full damage state. The peak strengths on the specimen machine are: 13.60MPa, 13.44 MPa, 14.92MPa, 14.69 MPa and 14.04 MPa, which are 54.02%, 51.18%, 96.57%, 98.25% and 58.11% respectively higher than the initial strength (see figure 8).

(6) Fracture failure stage: continue to apply the load, the damage degree of the specimen further increased, there are many cracks on the surface of the specimen, the main crack 1 has formed a macroscopic through plane, the internal damage of the specimen has reached the limit value. Finally, fracture failure occurred (see Figure 9).

The tests result showed that the initial crack strength ranges from 7.41 to 8.89MPa, with an average value of 8.32MPa. In general, the initial crack strength fluctuates in a small range, while the uniaxial compressive strength is more discrete. The reason is that the initial damage degree of the test piece is approximately the same, under the same mixing ratio, the manufacturing method and the same test conditions. With the expansion of the pores, the shear deformation of the pressure - tight crack is expanded and the crack is pulled apart. The component material of the whole specimen is in the state of unstable deformation and failure. It is difficult to analyze and explain the failure of the specimen because of the deformation of the component material, so the value of uniaxial compressive strength is more discrete. According to the crack propagation rate of the main crack ① propagation length of each specimen, it can be seen that the internal damage is a relatively stable process before the peak strength of the specimen is reached. At the stage of damage expansion, the crack propagation rate of each specimen is relatively large. It can be seen that the crack growth is faster and the damage development of the specimen is more rapid at this stage. After loading to the peak strength stage, the fracture propagation rate is relatively small, but the transverse direction of the main crack ① is obviously significantly widen and the branch fracture appears, indicating that the continuity of the specimen is seriously damaged. The material changes from a continuous medium to a discontinuous medium. It can be seen that the damage-fracture evolution during compression is actually the process of internal damage, elastic damage, damage manifestation, damage propagation, peak value and specimen fracture failure.

Owing to the ultrasonic wave velocity can reflect the relationship between internal damage and macroscopic fracture of specimen under uniaxial compression. in this paper, the variation of strain in the specimen during the loading process is used to establish the relationship between the strain change and the wave velocity, and the wave velocity-strain characteristic diagram during the compression process is obtained, and the damage evolution law of the specimen during loading is obtained. By analyzing the variation characteristics of the specimen from damage to fracture, and thus explaining the characteristics of damage and fracture evolution, see Figure 10 to 14.

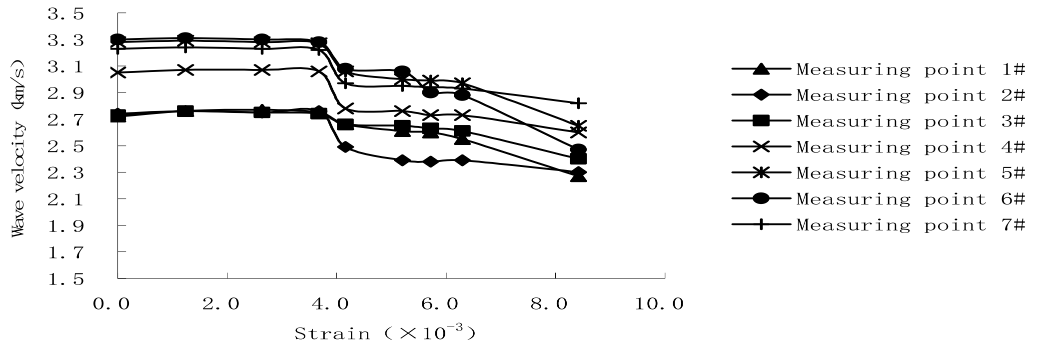


Figure 10. Relationship between wave velocity and strain during compression of the WZ-1 specimen.

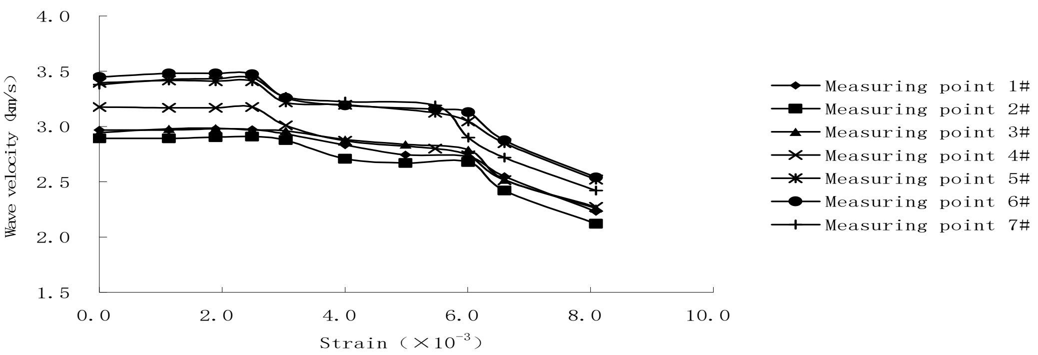


Figure 11. Relationship between wave velocity and strain during compression of the WZ-2 specimen

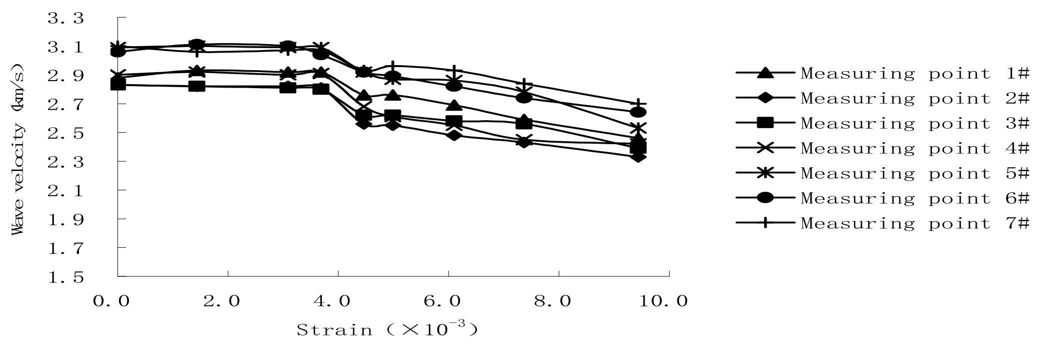


Figure 12. Relationship between wave velocity and strain during compression of the WZ-3 specimen

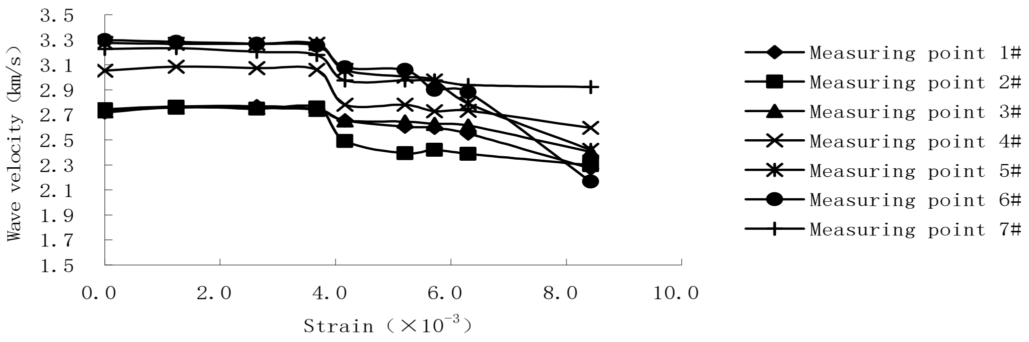


Figure 13. Relationship between wave velocity and strain during compression of the WZ-4 specimen

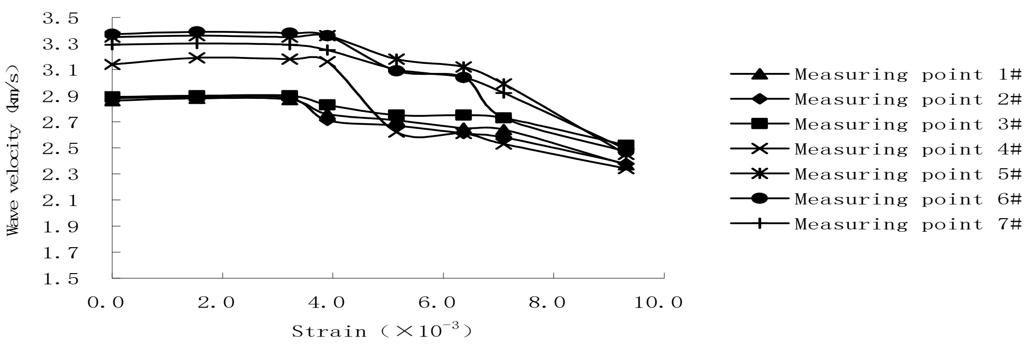


Figure 14. Relationship between wave velocity and strain during compression of the WZ-5 specimen

It can be seen from the wave velocities-strain diagram of five specimens (see figure 10 to 14) that each measuring point has a similar wave velocities-strain relationship. The general rules are as follows:

(1) The initial wave velocities of the measuring point 1#, 2 # and 3# are close to each other, the initial wave velocities of measuring point 5#, 6# and 7# are close to each other. The reason is that the measuring point 1#, 2# and 3# are arranged in the upper half of the specimen, and the measuring point 5#, 6# and 7# are arranged in the lower half of the specimen. During the forming process of the specimen, the upper part of the mortar will slip through the pores in the lower half due to the deadweight, and the evaporation of the upper part will be larger than that of the lower part during the curing process. Resulting in the upper half of the dense effect is not as good as the lower half, therefore, the initial wave velocities of the measuring point 1#, 2 # and 3# are smaller than the initial wave velocities of the measuring point 5#, 6# and7#.

(2) The initial wave velocity of the test point 4# is in the middle of the initial wave velocity value at other measuring points. The reason is that the measurement point 4# is arranged in the middle position of the specimen, the dense effect is in the upper and the lower half. So the above phenomenon occurred.

(3) The characteristics of the whole wave velocity-strain curve are as follows:

1) The initial defects in the specimens were partially propagated due to compressive stress, which make the wave velocity decrease, but the decrease was not obvious, and most of the microdefects were in a stable state. Some initial cracks will be closed under compressive stress, and the wave velocity

will increase, but the increase will not be small. Moreover, the microdefects are randomly distributed, so the propagating crack and the closed crack are also generated randomly. This results in no obvious change of the wave velocity with the increase of load before the crack appears.

2) The wave velocity decreases obviously when cracks appear on the surface of the specimen. There are macroscopic local cracks on the surface of the specimen, but not through the whole specimen. If the loading is stopped, the propagation of the local crack will be stopped.

3) As the load continues to be applied, it enters the stage of crack growth. The wave velocity of ultrasonic wave decreases sharply with the increase of strain, and the microcrack propagation and extension of the specimen is very unstable. There will be several macroscopic cracks on the surface of the specimen. The length of the crack is different and the distribution of the crack is random.

4) The crack continues to propagate rapidly, resulting in severe damage to the specimen, which can no longer bear the applied load. The rupture of the specimen leads to a downward trend of the whole wave velocities-strain curve. The measured wave velocity decreases sharply, when the specimen is damaged.

4. Conclusion

(1) The initial crack strength and uniaxial compressive strength were obtained by uniaxial compression test. The experimental results show that the initial crack strength of the specimen is in the range of 7.41 to 8.89 MPa with an average of 8.32 MPa, and the uniaxial compressive strength is in the range of 13.44 to 14.93 MPA with an average of 14.14MPa. In general, the initial crack strength fluctuates in a small range, while the uniaxial compressive strength is more discrete.

(2) According to the crack propagation rate obtained from the propagation length of the main crack ① of each specimen, it can be seen that the internal damage is a relatively stable process before the peak strength of the specimen is reached. At the stage of damage expansion, the crack propagation rate of each specimen is relatively large, and the crack growth rate is faster, and the damage development of the specimen is more rapid, and the crack propagation rate is smaller than that of the specimen at the peak strength stage. However, the transverse direction of the main fracture ① is obviously widened and the branch fracture appears. The material gradually changes from the continuous medium to the discontinuous medium. It can be seen that the damage-fracture evolution during compression is actually the process of internal damage, elastic damage, damage manifestation, damage propagation, peak value and specimen fracture failure.

(3) The wave velocity in the loading process of the specimen is measured by the ultrasonic instrument. The experimental results show that the wave velocities of the measured points do not change obviously with the increase of the load before there is no crack on the surface of the specimen. When cracks appear on the surface of the specimen, the wave velocities of the measured points decrease obviously with the increase of the load. With the gradual extension of the damage, the integrity of the specimen is seriously damaged, and the wave velocity of each measuring point obviously decreases.

(4) Through the obtained strain and wave velocity, the characteristic diagram of wave velocity-strain curve is drawn. The curves show that each measuring point has similar wave velocity-strain relationship, the initial wave velocities at measuring point 1#, 2# and 3# are close to each other. The initial wave velocities at measuring point 5#, 6# and 7# are close to each other, The initial wave velocities of the measuring points 4# are in the middle of the initial wave velocities of other measuring points. This is due to the uneven density distribution of the specimen.

Acknowledgements

This study in the paper was funded by The National Natural Science Foundation of China (No. 11272185, 51678067 and 51378521), and Chongqing Postgraduate Education Innovation Fund project funding (No. CYB18167).

IOP Conf. Series: Earth and Environmental Science **237** (2019) 032083 doi:10.1088/1755-1315/237/3/032083

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