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CT and AE Test Research on Concrete Damage Localization

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Abstract: CT scanning test and acoustic emission damage localization test were conducted under uniaxial compression in order to solve the technical problems of damage localization in concrete failure process, in addition to the porosity variation law, 3D meso model of concrete pores and cracks at different loading stages are obtained. A damage variable based on CT images and acoustic emission damage points is created. Research results show that the changes of porosity, pore volume and damage variable are consistent with loading process, the rapid increment of concrete pore volume and damage variable can be a precursor to the failure of concrete; 3D reconstruction of concrete images and acoustic emission damage location map was used comprehensively to observe and analyze the whole process of concrete crack development and evolution. A new method for the analysis of concrete crack evolution and localization of the damage was provided from the result.

Keyword: *concrete, 3D micro model; absolute porosity, damage variable, damage localization*

1. Introduction

Concrete is a kind of complex multi-phase composite material, initial defects such as micro cracks and pores generate in concrete structure in the process of pouring for the reason of hydration heat release, shrink, etc. The micro cracks expand to macro-cracks under external load or environmental factors, then lead to the decline of the strength, stiffness and eventually cause stability damage to engineering. The relationship between the macro performance indexes and failure characteristic parameters has been a technical problem in various fields [1]. The current research of concrete is based on the conventional mechanics test method, that is speculate the mechanical character of structural materials through comparative analysis of test data instead of using the change of the internal meso structure directly to explain the damage evolution process under the load[2]. Computerized tomography technology (CT technology) can reach dynamic nondestructive observation on the change of internal meso structure in concrete material[3-6], and CT images are visual basic information to establish the meso damage model of concrete[7,8]. Acoustic emission detection is a real-time dynamic nondestructive testing, which is highly sensitive to concrete defects. Degree of damage in concrete can be judged according to the tests, and this is of great significance to evaluate the concrete performance [9, 10].

The key of the research on concrete meso damage is to identify the existence of meso damage and the expand process of the damage effectively. CT is short as Computerized Tomography, compared with other methods, CT test has its incomparable advantage on nondestructive detection and real time observation in concrete material under various loading condition. CT images can be obtained by scanning the sections of concrete with industrial CT scanning. Both of the meso structure of concrete and its changing process can be analyzed through CT images, then the law of evolution and expansion for damage in concrete failure process is the key to the CT images analysis. Therefore, CT test is an effective mean to detect the meso pore structure, crack initiation, propagation and coalescence with no damage. In view of this, quite a lot of research work, from different views with different research methods, was done by scholars at home and abroad.

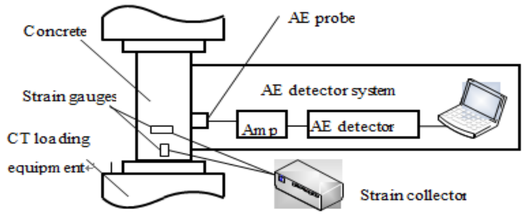
Foreign researches started quantitative study on concrete CT detection in 1980s. Morgan [11] is the first to use the medical CT to run CT scanning on concrete specimens, and concrete section images for aggregate, mortar, crack was obtained clearly. Chotard T J [12] got pretty effect on the change of the internal structure for cement while hydrating. John S Lawer[13] analyzed failure mode of concrete surface with digital image correlation technique, and the research conclusion could reflect the internal structural change during cracks evolution process, besides, the influence of aggregate shape, crack shape on concrete strength, toughness was discussed based on CT images after concrete cracking. Wong R C K [14] conducted uniaxial compression CT test to normal and high strength concrete cylinder specimens, then the evolution process of pore under different stress state was studied. Meanwhile, a large number of concrete CT tests were carried out in China, and abundant research results were obtained: academician Chen Houqun using CT real time scanning to observe the meso failure process of concrete under the uniaxial compression, then the whole process CT images of internal meso cracks from initiation, expansion to coalescence was got, finally, quantitative analysis methods based on concrete CT images was established in the cracks area. Ding Weihua [15] used medical CT machine and special loading equipment to explore morphology change characteristics of micro cracks under the condition of different loading rate by images analyses and the distribution of CT number. Wu Liqin [16] described the damage property of concrete materials, and the failure process in concrete was revealed in meso view, that is initial crack stress and crack propagation process. Liu Hankun [17] used CT technique to scan concrete specimens and then reconstructed the images with Mimics software; finally the 3D geometric model of concrete specimens can be got. The plastic damage model of concrete 3D numerical specimens was introduced to simulate the uniaxial tension and compression loading process and then the rationality of 3D numerical model was identified.

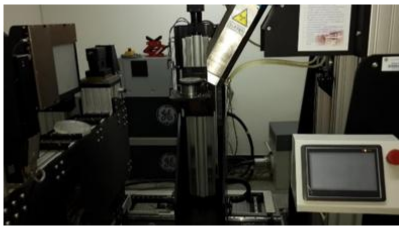
Although researchers at homeland and abroad have done much research work based on CT test [18-28], it is rare to see do quantitative analysis on crack initiation and propagation mechanism of concrete by using acoustic emission and CT combined. CT scanning has obvious advantage on real-time and nondestructive detection to internal structural change process, but its disadvantage is for both of the equipment and scanning cost are much higher. The previous real-time monitoring tests are carry out CT scanning after stopping loading when the loading reaches a specific stress stage. The test results may not ideal or the cost may increase if the stresses when scanning are not properly selected. As the unique passive detection technology in nondestructive testing, acoustic emission detection technology can monitor and evaluate the whole concrete structure in real-time, acoustic emission signal can reflect the change situation of the internal structural damage accurately except for its defects that can't be observed evolution of pore and damage in structures directly. Considering their advantages in detection, tests on combination of acoustic emission and CT can be conducted. Stop loading when acoustic emission signal prompts there are new cracks generated or the old cracks expanded, then explore the relationship between CT scanning images and acoustic emission by scanning concrete with CT.

In this thesis, the meso structure of concrete and its changing process was analyzed with the feature of CT images, and then the order of damage evolution in concrete is described by damage variable based on CT images and acoustic emission damage points.

2. CT scanning test and acoustic emission damage location in concrete under uniaxial compression:

The process of cracks propagation was observed with X-ray CT scan detection system in State Key Laboratory of coal mining, China University of Mining and Technology (Beijing), acoustic emission signal data acquisition system and 3000kN ultra high rigidity servo testing machine under uniaxial compression, the schematic diagram of the test system is shown in Figure 1.





CT scanning system

High rigidity servo tester of 3000kN

SAEU2S physical map of AE collection box

Figure 1: *Sketch of experimental system*

Different amount air entrained agent was added when making concrete blocks, then 4 groups concrete specimens, with initial porosity of 1.1%, 3.3%, 6.7% and 9.2%, were obtained to utilize in this test. The height and the radium of the concrete cylinder blocks are 190mm, 50mm. The mix proportion of concrete specimens used in the test is shown in table 1.

Table 1: *Mix proportion of concrete specimens in test*

The amount of materials in per cube meters concrete			
Cement (kg)	Water (kg)	Sand (kg)	Coarse aggregate (kg)
327	189	755	1133

Displacement control methods were used in the test and its loading rate was 0.2mm/min. The scanning work was done in the range of upper 100mm, and it is needed add that the scanning interval is 0.2mm. Repeat the work like this until test specimens reach the peak strength. Continue with the loading after the scanning. The loading curve of the test is shown in Figure 2. The acoustic emission machine was introduced to collect the test data in the whole loading process.

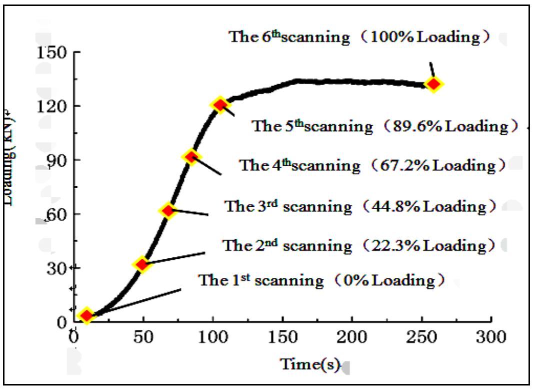


Figure 2: *Loading-time curve*

As shown in Figure 2, 5 cyclic loading tests were carried out on concrete test specimens, and the loading interval was 30KN in every two adjacent load, finally the ultimate strength was 134KN.

There are 6 stages of scanning on concrete test specimens, included the initial stage, as shown in Table 2.

Table 2: *The load corresponding to the six scanning time of the concrete specimen*

CT scan times	Loading(kN)	Percent of the peak strength
1st scan	0	0%
2nd scan	30	22.3%
3rd scan	60	44.8%
4th scan	90	67.2%
5th scan	120	89.6%
6th scan	134	100%

There are 499 CT scanning images in every test specimen, 5 CT scanning images are chosen to conduct the analysis due to the limited space, as shown in Figure 3.

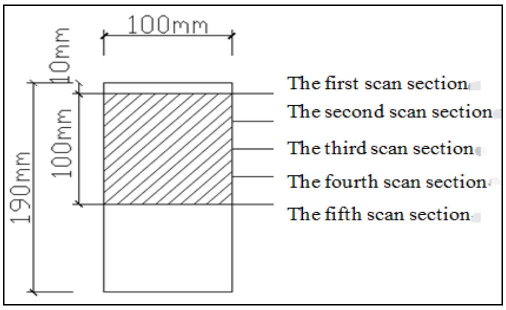


Figure 3: *Concrete sections map of CT scan*

CT scanning test and acoustic emission test were conducted in 4 groups concrete test specimens under uniaxial compression, then the load-time curve, CT images and acoustic emission parameters were collected during the loading process. The concrete test specimens with initial 9.2% porosity are chosen to analyze in this thesis as the limited space. The CT scanning images of initial state, 30kN, 60kN, 90kN, 120kN, and 134kN when destroyed are listed in Figure 4.

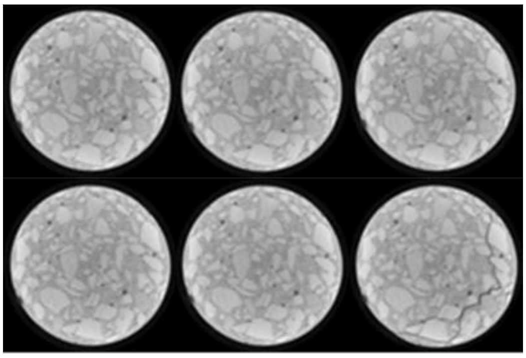


Figure 4: *CT scanning images of concrete in different loading*

As shown in Figure 4, there are no obvious cracks during the early loading stages in test specimens with 9.2% initial porosity, and the early loading stages can be considered as a compaction process for the pores for the reason of its relative large porosity. The internal micro cracks connect with micro pore and eventually the main visible cracks generate until the test specimens are destroyed.

3. 3D meso scale model of concrete CT image:

The Amira software was used to reconstruct the meso structure in 3D after the CT images were divided [13]. It is needed to say that Amira is a 3D visual modeling software system, and two basic components of the system, data and modules with different function, are included. The data are processed with modules by their connection with each other, and then the visualization of scientific data can be realized in various application areas, such as medical science, materials science, geophysics and engineering etc. The result of the 3D reconstruction shows in Figure 5.

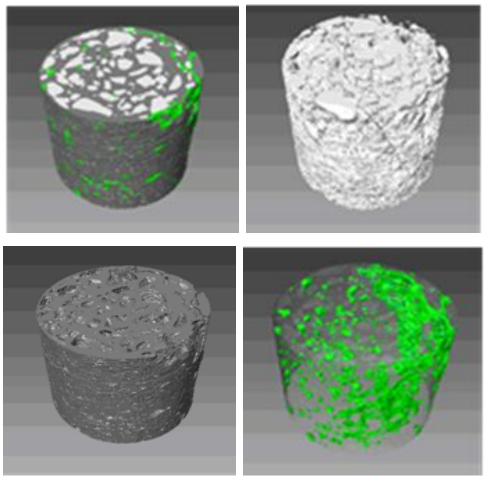


Figure 5: *From left to right: test specimens, aggregate, mortar, spatial distribution of cracks*

In Figure 5, the distribution of aggregate in concrete 3D reconstruction model accords with the original CT images, and the volume of each component is almost the same with the mix proportion of concrete. The visualization of cracks realizes with transparent processing, and the spatial shape is relatively clear, finally the cracks structure in concrete materials is shown in a real way.

Subsequent work like image segmentation and extrusion of cracks can be done with Amira Software, and the Figure 6 is the characteristic change chart of cracks and pores.

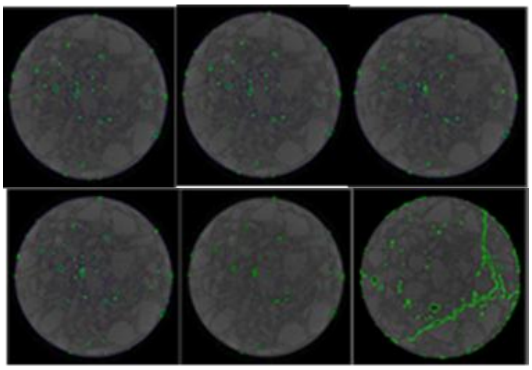


Figure 6: *Threshold segmentation map of Concrete pore under*

As shown in Figure 6, there are cracks and pores in concrete surrounded by green area, then the cracks and pores show clearer in CT images through segmentation and extrusion. CT images in the upper of the test specimens from the 20th to 470th CT images were selected to gather statistical information on the volume of pores and the porosity in every 90 CT images, the relation graphs of pore volume, Pore ratio with pressure can be seen in Figure 7, Figure 8.

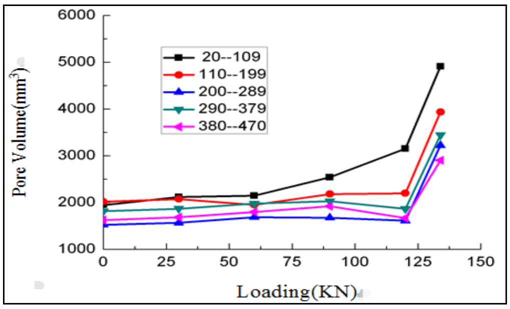


Figure 7: *Pore volume-pressure map*

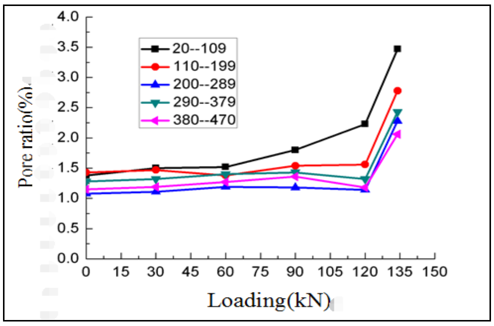


Figure 8: *Pore ratio change with loading*

In Figure 7 and Figure 8, the changing law of pore volume, porosity with loading in every CT scanning pieces is almost the same under uniaxial loading. The loading curve decreases slight in the start loading stage but keeps nearly a straight line, as a result that the test specimens is in the elastic stage. In this stage, initial pores are compressed then the volume of the pores and porosity reduce. With the increment of the load, the micro cracks expand gradually, certainly, the volume of the pores enlarges. When the load approaches the peak strength, there are obvious cracks in test specimens from CT images, and then the volume of pores and porosity achieve the maximum, thus, the phenomenon that the rapid increment of the volume of pores and porosity indicates the failure of concrete test specimens.

4. Damage location analysis with Acoustic emission:

The test specimens with 9.2% initial porosity are chosen as the sample to complete the damage location with acoustic emission machine, and this lays great foundation to the setting parameters. Choosing proper threshold and time parameters is absolutely vital for extracting the time difference of occurrence from each acoustic emission signals. It is appropriate to set the threshold in the range between test noise and experimental noise. HDT is used to confirm the end of the signal, and one signal will be divide into several if set excessively short, then several signals will be merged into one instead.

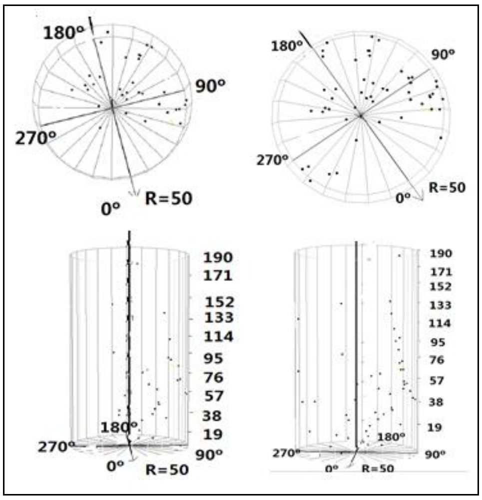
In order remove the reflected wave, HLT can be introducing. Practice shows that the threshold and time parameters should be considered comprehensively in damage location rather than separately, especially in composite material like concrete. Besides, the input of the wave velocity also influences the accuracy in damage location. 4 groups test specimens with different porosity were calibrated with velocity. The result showed that the change of the wave velocity has limited impact on location; therefore, inputting the former velocity directly, rather than taking this factor into consideration, is reasonable in civil engineering.

The distribution of the detectors is very important to damage locating; however, there are 4 detectors at least in 3D location. The more the detectors are, the more accurate the damage location is in theory. The distribution of the detectors focus on the lower part of test specimens as the upper part are used for CT scanning, and this makes influence to damage location, the main cracks, however, is pretty satisfied. The environmental noise is confirmed to be 70db through observation of the acoustic emission data. The data for test specimens with 9.2% porosity was collected when the cracks expanded obviously: the wave velocity was input 3000m/s, and the threshold was enter as 55db, 75db, 100db separately, meanwhile, time parameters were adjusted before the test. The location points can be considered as effective when they appeared in the cracks shown in the CT images. The modified process is shown in Table 3.

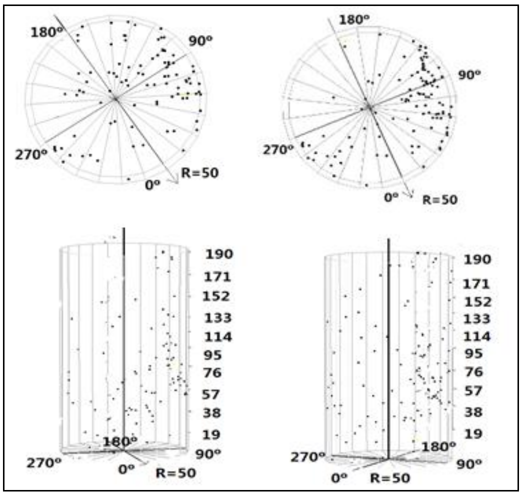
Table 3: *The adjustment of AE parameters*

CH (db)	HDT (μs)	HLT (μs)	Location points number	Qualified Number
100	2000	2000	18	14
100	1500	1500	29	26
100	1000	1000	26	20
100	300	500	66	54
100	200	300	120	93
75	300	500	40	31
75	200	300	56	44
75	100	200	97	82
55	300	500	12	9
55	200	300	32	26

As shown in Table 3, there are less damage points when the threshold is 55db. The reason for this is that the threshold selected is lower than the value of environmental noise, and this caused the effective signals to be drowned, finally these signals can be extracted. Considering that the greater the magnitude of the signal is, the greater the effect on strain and cracking of the material is coupled with the factor that concrete is a composite material, the accuracy of damage location based on acoustic emission is limited. The above factors are taken into account, then settings are made as follow, the threshold: 100db, PDT: 150us, HDT: 300us, HLT: 500us after take the absolute amount, relative proportions and location rate of the effective location points into comprehensive consideration. The above work is carried out, and then the location of damage and cracks is clear, finally lay foundation to the accurate damage location with ultrasonic instrument. On the other hand, there are also some points with high energy do not appear in the macroscopic crack area. Once the cracks appears in engineering, safety measures can be taken in the area. In order to reduce the influence of echoes, the maximum and minimum of energy can be removed, and this also makes the macroscopic crack clearer than before. After the adjustment, the location of the damage points at different stress stages shows in Figure 9.



23% of peak value *67% of peak value*



90% of peak value *peak value*

Figure 9: *AE damage location map in concrete specimens under different stress stage*

As Figure 9 shows, the fact that the failure surface in the damage location map is clear and keeps correspondence with the crack in CT reconstruction model helps to track the location of the damage point accurately, and it can satisfy the requirement to find the "weak face" in structure and materials.

The effective area of concrete is calculated in Amira by determining counting the damage point numbers in the central undamaged area, shown as D_2. The remaining part is considered as the damaged part is counted in the similar way, designated as D_1. The definition of damage variable is $H=D_1/D_2$. The loading-damage curve of the concrete specimen is shown in Figure 10.

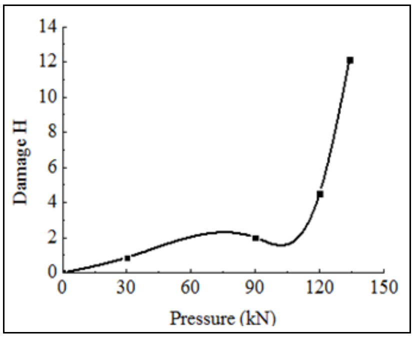


Figure 10: *Pressure-damage curve of concrete test specimen*

As shown in Figure 10, the damage points, based on the damage variable of acoustic emission damage location, in the main cracks area after destruction were compared with the damage points in other area, then the result showed the order of the concrete test specimens. Before 30% of the peak load, the damage variable is less than 1 which indicates the damage location is in disorder; When the load reach 80%~100% of the peak load, the damage curve rise steeply, then the cracks appears, finally, the test specimens instability fails. The Press-damage curve reflects the whole process from disorder to order, and it keeps in pace with press-porosity volume cure.

Though the comprehensive analysis on damage location map with acoustic emission, press-porosity volume cure and the load-time curve, that fact can be get as follows. Before 30% of the peak load, the damage points are disordered, and the damage variable in concrete is relative small, then the volume of the pores in material increase slightly. After the load is steadily increase to 30% of the peak load, the damage points appear in order around the macro failure surface, then the damage variable start to grow, so do the volume of the pores; the change of the pores distribution and the center coordinate are also not obvious, and all of this phenomena indicate that the test specimens are destroying steadily; when the load reaches the peak, the stress of concrete test specimen is almost unchanged, while, the damage points around the macro failure surface increase rapidly, then the damage variable and the volume of the pores show a marked trend of growth.

5. Conclusion

(1) CT images and damage location map from acoustic emission are used comprehensively to provide new methods for the concrete analyses on the evolution process of cracks and damage location.
(2) The damage variable is established based on CT images and acoustic emission damage points; then the set of the 3D meso model supplement the traditional stochastic mathematical model in concrete. The 3D model set reflects the relationship between meso structure in concrete and macro characteristics, and this lay foundation to the concrete research on damage mechanism.
(3) The rapid increment of the pore volume, porosity and damage variable can be regarded as destroy of concrete test specimens, therefore, the phenomenon can be a sign of destroy in concrete.

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