Investigation of Initial Rock Damage and its Effects on Uniaxial Compressive Strength

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Abstract. This study investigated the initial rock damages and their effects on the uniaxial compressive strength of soft rock (claystone) and hard rock (marble) using Computerized Tomography (CT) scanning. The soft rock (claystone) samples were initially damaged before sampling. The samples were taken from three test areas with different levels of deterioration. These areas were initially subjected to different deteriorating conditions. In Area 1, the rock was exposed to natural air, called the uncovered test area; In Area 2, the rocks were wetted for three days by watering, drying, and exposing it to the sun/wind, called a wetting-drying test area. This process was conducted by wetting and drying the rocks for three days each; and in Area 3, the rock was covered with a concrete slab (in-place poured concrete), called a concrete covered test area. These different sampling methods damaged the hard rocks (marble). CT scanning experiments showed the recorded average CT numbers of the rock samples (from the highest to lowest) are: the concrete covered area, the uncovered area, and the wetting-drying area. The test results of the soft rock samples also demonstrated that a higher average CT number corresponded to a higher uniaxial compressive strength. In addition, the average CT number for soft rock undergoing different degrees of initial damage exhibits a certain regularity. The average CT number of the soft rock confirmed induced damages by the deteriorating condition. Using a nondestructive sampling method for the hard rock led to a significantly lower degree of initial damage than the samples obtained by the conventional sampling method. The marble samples obtained by the nondestructive sampling method exhibited higher average CT numbers and uniaxial compressive strength than the samples obtained by conventional sampling method.

1. Introduction

In recent years, many researchers have applied CT technology to study fracture development in rocks. After the first application of CT scanning technology by Withjack [1] to study geological material properties in the late 1980s, this technology has been widely used in geoscience and geotechnical engineering. Yang Gengshe [2, 3] et al. analyzed the distribution characteristics of CT numbers using rock CT images. It was discovered that the histogram of the CT numbers exhibited single-peak and multi-peak curves for the unfractured rock and fractured rock samples, respectively. Ge Xiurun et al. [4] conducted a dynamic CT real-time scanning test to study microscopic damage expansion in coal-rock specimens under triaxial and uniaxial compression using triaxial loading equipment, where the scanning was performed under loading conditions. They reported that there was a threshold for fatigue failure of the rock on a microscale. Ding Weihua [5, 6] proposed the concept of CT scale fractures. Wu...
Yanqing and Cao Guangzhu [7] studied the propagation and seepage characteristics of small cracks in rocks at CT scale, established a formula for the rock porosity based on the CT number, and concluded that the threshold values of small rock fractures are different due to the difference in rock strengths. Ren Jianxi et al. [8, 9] studied the microdamage propagation in sandstone for the entire failure development under triaxial or uniaxial loading. He theoretically derived the concept of density damage increment, quantitatively described the density damage of the rock, and established the quantitative relationship between volumetric rock deformation and density damage increment. Despite many successful applications of CT in studying rock samples, several other areas require critical investigation. For example, only a few studies employed CT tests to examine the degree of the initial damage effects on the mechanical properties of the rock and conducted real-time screening internal fracture development in the rock under different loading conditions. Hence, this study presents a CT scanning application to investigate the effect of initial damage in soft rock (clay rock) and hard rock (marble) samples on their uniaxial compressive strength.

2. CT scanning mechanism for rock

In the experiments, a computer cross-sectional X-ray CT test was performed using Somatom CT system in the Key Laboratory of Rock and Soil Mechanics and Engineering of the Ministry of Water Resources at the Yangtze River Scientific Research Institute. The Sensation 40 medical spiral CT machine was manufactured by Siemens, Germany, with a spatial resolution of 40 layers (Figure 1). Rock CT images can give the degree of X-ray absorption of each part of the rock in the form of digital images. The value of each pixel is the CT number. The grayscale represents the size of the CT number on the CT image. The CT number is proportional to the corresponding rock density according to the physical principles of CT. The bright color of the CT image indicates the high-density area of the rock, and the dark color indicates the low-density region of the rock. The density of each part is different and proportional to the X-ray absorption coefficient because the mineral composition or structure in the rock is not uniform. Therefore, the CT image can also be regarded as the density distribution map of the scanned rock area. The activity of microholes and microcracks in a specific area of the rock will inevitably cause the density of that area to change. Conversely, the abnormal density changes in a particular area of the rock can also reflect the collective effect of microcavities and microcracks in this region. This is the principle of using CT images to observe rock mesoscopic cracks. In addition to CT image analysis, the quantitative analysis of CT numbers is also essential. The mean, variance, and distribution of CT numbers in the scanning section can better indicate the critical characteristics in rock material damage.

Quantitative analysis of rock CT numbers helps to further establish a relationship between the CT numbers and variables describing rock damage [3]. A larger CT number indicates a less damaged rock sample, while a smaller CT number indicates a more damaged rock sample. About five scanning cross-sections were selected evenly from the top to the bottom of each rock sample to obtain the distribution of CT numbers on different cross-sections of the rock sample. The CT number distribution on each cross-section is counted from the inside to the outside according to concentric circles (Figure 2), where 3 to 4 concentric circles are generally selected for each cross-section. The statistical parameters: the average CT number and the variance of the CT number in each concentric circle are used to determine the damaged area and relative degree of the damage in the rock samples. The CT image can show the orientation of initial cracks in the rock samples. If there are no obvious cracks, the deterioration of the rock sample can only be reflected in the average CT number and the variance of the CT number. Due to word limitations, this article only conducted statistical analysis on the CT numbers of the outermost circle.
3. CT test results on initial damage in soft rock (clay rock)

In the experiment, the clay rock was selected for CT scanning. The bedrock in the selected area was initially damaged to different degrees by undergoing different deteriorating conditions. The soft rock (claystone) samples were initially damaged at the site before sampling. Therefore, the sampling site was specially treated for the study. At the designated sampling site, the top 1-meter rock was excavated and removed. The site was then divided into three areas such that the in-place rock was subjected to three different deteriorating conditions: In Area 1, the rock was exposed to natural air for four months, called the uncovered test area; In Area 2, the rocks were wetted for three days by watering, drying, and exposing it to the sun/wind, called a wetting-drying test area. This process was conducted by wetting and drying the rocks for three days each for four months; and in Area 3, the rock was covered with a concrete slab (in-place poured concrete) for four months, called a concrete covered test area. The samples of the soft rock were taken from these test areas separately.

3.1. CT scanning results on damaged rock sampled from the natural open test area

The first batch of samples from this area was taken immediately after the excavation. The second batch was taken four months later after natural exposure.
The samples from the uncovered test area were analyzed. Figure 3 shows the distribution of the average CT numbers in the statistical circles of each rock sample in the first batch. Figure 4 shows the distribution of the average CT numbers in the outermost statistical circle of each rock sample in the second batch. Their CT cross-sectional diagrams, longitudinal section views, and perspective views are shown in Figures 5 and 6. The average value of CT numbers for the rock sample in the second batch is lower than those in the first batch, indicating that the rock samples were damaged by long-lasting weathering at the site. However, there are no significant differences in the average CT numbers for the rock samples obtained at the same depth in the area, depicting that at the same depth, the degree of damage of rock samples is the same. Therefore, it is believed that the degree of initial damage of the rock does not vary significantly with the increase of sampling depth.

3.2. **CT scanning results on damaged rock sampled from wetting-drying deterioration area**

The rock sample in this area was initially damaged by wetting and drying alternatively by natural exposure for four months after the excavation. Figure 7 shows the distribution of the average CT numbers in the outermost statistical circle of rock samples taken at different depths, while Figure 8 shows the CT images of the rock samples from this area. From the results, no clear distinction could be made between the average CT number of the rock samples at different depths. This reconfirms that the degree of initial damage of the rock does not vary significantly with sampling depth.

![Figure 5. CT cross-sectional diagram, longitudinal section view, a perspective diagram of the typical rock sample (working condition, the open area maintained naturally after excavation of 1 m)](image)

![Figure 6. CT cross-section view, longitudinal section view, and perspective view for a typical sample (Working condition, the open area maintained naturally after natural exposure of 4 months following excavation of 1 m)](image)

![Figure 7. Distribution diagram of average CT numbers in the outermost statistical circle of rock sampled at different depths (samples were undergone wetting and air-drying cycle during natural exposure of 4 months after excavation of 1 m)](image)
3.3. *CT scanning results on damaged rock sampled from the concrete cover test area*  
Figure 9 shows the average value of CT numbers in the statistical circle of the rock samples from this area, while Figure 10 shows the CT images of the rock samples. Here again, only slight differences were observed between the average CT numbers of rock samples obtained at different depths and thus reiterating that the degree of initial damage in rock does not vary with sampling depths significantly.

Figure 9. Distribution diagram of average CT numbers in the outmost statistical circle of rock sampled at different depths (samples were from the area covered by in-place poured concrete during natural exposure of 4 months following excavation of 1 m)

Figure 10. CT cross-sectional view, longitudinal section view, perspective view (rock samples were from the area covered by in-place poured concrete during natural exposure of 4 months following excavation of 1 m)

3.4. *Comparison of uniaxial compressive strength for rock samples at different degrees of damage*  
Comparing the CT results of the rock samples with the same degree of damage from the natural open test area, it was noted that the average CT numbers of the rock samples initially damaged by natural exposure for four months after the excavation is significantly lower than the average CT numbers of the rock samples taken immediately after the excavation (Figures 3 and 4). This clearly indicates that the long-term weathering has deteriorated the rock. The degree of initial damage is higher in the rock
subjected to deterioration for four months (Figures 5 and 6), consistent with the laboratory test results of mechanical rock properties. The uniaxial compressive strength is one of such properties. It is obtained from the uniaxial compressive strength test, where it decreased for rock samples that underwent natural exposure, indicating that the rock has deteriorated after a long weathering period. The average CT number of the three rock samples in descending order is the concrete cover area, the natural open test area, and the wetting-drying area. The degree of rock damage is consistent with laboratory test results of mechanical rock properties. In addition, in descending order, the uniaxial compressive strengths of the rock samples are the concrete cover area, the natural open test area, and the wetting-drying area. This shows that the rock samples with the least degree of damage exhibited higher uniaxial compressive strengths and average CT numbers. The test results showed that the uniaxial strengths of claystone under different damage degrees vary in a certain regularity. The relationship between the rock’s CT numbers and the corresponding uniaxial compressive strengths is shown in Table 1.

| Table 1 Rock’s CT numbers with corresponding uniaxial compressive strengths |
|---------------------------------------------------------------|
| **Type of rock** | **Soft rock** | **Hard rock** |
| **Initial damage condition** | **Maintained naturally** | **Undergoing wetting and air-drying cycle** | **Covered by in-place poured concrete** |
| **Average CT number** | 1791 | 1787 | 1805 |
| **Uniaxial compressive strength (MPa)** | 5.83 | 5.23 | 7.63 |

4. CT test results on initial damage of hard rock (marble)

Marble was used as the hard rock material. The samples were initially damaged using different sampling methods. Rock samples were obtained from three boreholes C, D, and Y, where boreholes C and D are for nondestructive sampling while borehole Y is for conventional sampling. On-site nondestructive sampling was conducted using the double rods drill sampling technique by gradual and controllable relief of the stress in the rock sampling area. The procedures are to select a sampling area in the field, then use drilling and cutting methods to form a drill shaft with a confined boundary to relieve the rock mass’s stress in the sampling area, and then obtain the rock samples. These rock samples are subjected to a uniaxial compressive test for uniaxial compressive strength.

4.1. CT scanning results on nondestructive sampling and conventional sampling of marble

Figure 11 shows the distribution of the average CT numbers of the rock samples. The horizontal axis represents the number of rock samples, while the vertical axis represents the average CT numbers. The average CT numbers on the statistical circles for the samples from boreholes C and D are significantly greater than those from borehole Y except rock samples of group number 2.

The average CT number of each rock sample obtained from boreholes C and D has no significant differences, while the rock sample obtained from borehole Y varies greatly. This indicates that the
individual rock samples from borehole Y are quite different. In addition, the initial damage of rock for boreholes C and D is lower than those for borehole Y. Statistics show that CT numbers on the inner and secondary-inner circles of the rock sample also show similar patterns as those on the outer and middle circles. It showed that the entire rock sample from borehole Y was seriously damaged due to the sampling technique. Based on the CT results and analyses of rock samples taken by nondestructive and conventional sampling techniques, it is suggested that the inner part of the rock sample (i.e., within cir3) is less affected by sampling damage.

4.2. Uniaxial compressive strengths for marble samples by nondestructive sampling and conventional sampling

A total of 7 rock samples obtained by nondestructive and conventional sampling techniques were tested for their uniaxial compressive strengths using the MTS815 rock mechanics test system. From Table 4.1, the uniaxial compressive strengths of the marble samples obtained by the nondestructive sampling method ranged between 95.2 and 107.6 MPa with an average value of 98.4 Mpa, while those obtained by the conventional sampling method ranged between 95.4 and 96.3 MPa with an average value of 95.9 Mpa. This is consistent with the CT test results. The CT numbers and uniaxial compressive strength values of the marble samples obtained by the nondestructive sampling method are higher than those obtained by the conventional sampling method. This indicates that the degree of initial damage of the rock affects its uniaxial compressive strength. The CT numbers of the rock samples with corresponding uniaxial compressive strengths are shown in Table 2.

| Borehole | Sample Number | Sampling Depth (m) | Diameter of Specimen (cm) | Uniaxial Compressive Strength $s_0$ (MPa) | Average value of Uniaxial Compressive Strength $s_0$ (MPa) | Average CT number |
|----------|---------------|--------------------|---------------------------|------------------------------------------|--------------------------------------------------|------------------|
| D (nondestructive sampling) | D25-2 | 12.45-12.67 | 4.98 | 95.20 | | |
| | D28 | 13.72-13.87 | 4.93 | 107.60 | | |
| | D30 | 15.68-15.86 | 4.93 | 96.50 | 98.4 | 2380 |
| | D31 | 16.10-16.23 | 4.97 | 95.80 | | |
| | D35 | 17.40-17.58 | 4.96 | 96.90 | | |
| Y (conventional sampling) | Y3-2 | 9.97-10.37 | 4.92 | 96.30 | 95.9 | 2345 |
| | Y4-2 | 6.06-6.36 | 4.92 | 95.40 | | |

5. Summary and discussion

This study presents the investigation of initial damage in soft (claystone) and hard rocks (marble) and their effects on uniaxial compressive strengths using CT scanning.

The soft rock was initially subjected to several deterioration conditions where the bedrock was scheduled to be sampled. The initial damage of hard rock was also accomplished using different sampling techniques. The results showed that the degree of initial damage of the rock has a significant impact on the uniaxial compressive strength. Rock samples with a lower degree of initial damage have higher CT numbers and higher compressive strengths and vice versa.

(1) By analyzing the CT scanning test results for the soft rock samples initially damaged by undergoing three different deteriorating conditions in the open, wetting and drying, and concrete cover test areas, it was noted that the average CT numbers of the rock samples taken after natural exposure of four months from the time of excavation are lower than those of the rock samples taken immediately after the excavation. This indicates that the degree of damage is affected by long weathering periods. In addition, no significant differences were observed in the average CT numbers of rock samples taken at different depths in the three test areas. Also,
the average CT number of the three rock samples in descending order is the concrete cover area, the natural open test area, and the wetting-drying area. The average CT numbers of clay rocks with different degrees of damage exhibit a particular variation.

(2) Analyzing the CT scanning test results for the hard rock samples initially damaged by different sampling techniques suggested that using a nondestructive sampling technique leads to a lower degree of initial damage in hard rock samples than conventional sampling techniques. The degree of initial damage of the rock affects its uniaxial compressive strength. The marble samples’ CT numbers and uniaxial compressive strengths using the nondestructive sampling are higher than the conventional sampling.

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