Oedometric compression of an assemblage of crushed particles

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ABSTRACT
One-dimensional compression tests on crushed granite samples have been conducted in a 20-cm diameter oedometric cell. A systematic investigation was carried out on the factors that influence the collapse of an assemblage of uniform crushed rock particles of different size ranging from 20 mm to 40 mm. Specimens were loaded in following conditions: air-dry, flooded and under water-pressures of respectively 100 kPa and 200 kPa. The amount of particle breakage was established from grain size analyses before and after loading. The experimental observations are discussed in detail to explain the role of water and those of water-pressure on rockfill settlements and particle breakage.

RÉSUMÉ
Des essais de compression sur des échantillons de granulats en granit ont été réalisés dans une cellule oedometrique de 20 cm de diamètre. Une étude systématique a été effectuée sur les facteurs qui influencent le broyage des particules dans un assemblage uniforme des grains de dimensions variant de 20 mm à 40 mm. Les spécimens ont été chargés dans les conditions suivantes : état sec, état saturé et état saturé sous une pression interstitielle de 100 kPa et 200 kPa. Le broyage de particules a été définie par des analyses granulométriques avant et après le chargement. Les observations expérimentales sont discutées en détail pour expliquer l'influence de l'eau et de la pression interstitielle sur le tassement des enrochement et le broyage des particules.

1 INTRODUCTION

There is widespread field evidence which shows that wetting may induce large settlements in rockfill structures. This is a well-known phenomenon which has received a continuous interest ever since the use of rockfill in dams and, more particularly, since the beginning of the 20th Century. In large earth and rockfill dams rapid collapse settlements have been associated with water impoundment.

Collapse phenomena of coarse granular aggregates have been observed in dams, embankments but also in the Laboratory (Sowers et al. 1965, Marsal, 1973) when testing specimens of compacted gravel. Nobari & Duncan (1972) worked on one-dimensional and triaxial compression tests on crushed argillite. Sieve analysis carried out before and after flooding the sample showed that during collapse some particle crushing occurs.

Oldecop and Alonso (2001) carry out oedometer tests with relative humidity control on a rockfill-type material. They observed that the relative humidity of 100% within the rockfill voids leads to a collapse strain equal to that observed in flooded specimens. Also, any situation leading to a change in water content of the rock particles is enough to cause collapse deformations.

Some researchers have studied subcritical crack growth in granite. Kwok et al., (2006) carried out four-point bending tests on granite specimens in the environments of air, water and dilute sulphuric acid (pH value of 2). The log-log plot of the crack growth rate, v, versus normalized SIF (Stress Intensity Factor), K_I/K_{IC}, are shown in Figure 1.

This can be explained with the theory of stress corrosion (Michalske and Freiman. 1982). Atkinson and Meredith (1987) state that the strained inter-atomic bonds at the tip of a crack are more vulnerable to the attack of a corrosive agent, such as water, than the unstressed material away from the tip. The corrosion reaction produces a weaker material, which is broken at lower K_I values than the uncorroded material (Figure 1).

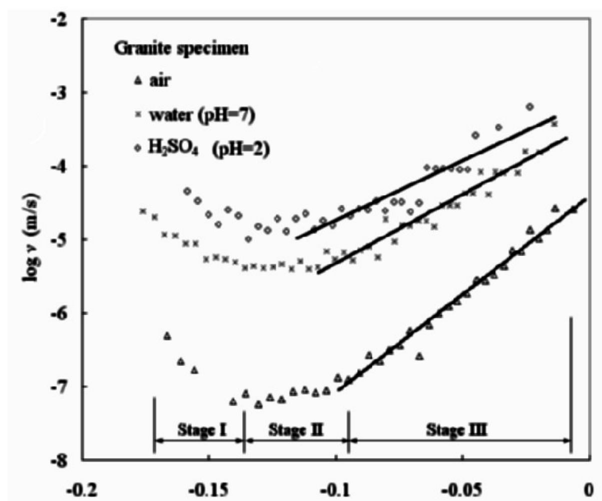

Figure 1: Log (K_I /KI_C) – log v curve for granite using four-point bending test (after Kwok et al., 2006).

It is possible to consider a rockfill with two sets of voids. A set of large voids is formed by the inter-particle spaces. Rock particles have their own natural porosity, and hence a second set of very much smaller voids can be identified within the rock particles named rock pore. The action of water contained within the rock pores has a determinant role on rockfill deformation and particle breakage. It was thought that the tests in which the water pressure of rock pores could be controlled would provide a better insight into rockfill behaviour. Such tests were performed on a rockfill type material using a water pressure control technique.

The focus of the present paper is on the factors that influence the collapse of rockfill upon flooding and under different water pressure level. This work includes one dimensional compression test on crushed granite. Sieve analysis were carried out before and after each test to determine the amount of grain breakage during tests. The experimental results are discussed in detail to explain the role of water and those of water-pressure on rockfill settlements and particle breakage.

2 EXPERIMENTAL SETUP

The oedometer test is widely used in practice to provide the parameters that are required to estimate the settlement, and rate of settlement on soft soils. However, the need to understand the deformation characteristic of coarser materials (eg. rockfill) extended its use to the study of granular media. Consequently, there was a continuous effort to develop larger consolidation cells in order to test specimens with gradation close to field and subject them to representative levels of load.

2.1 Testing equipment and specimen preparation

In the oedometer, lateral movement of the grain is prevented by containing the grain in a stiff metal ring so that only vertical (one-dimensional) grain movements are possible. An oedometer test program was carried out in a 200 mm diameter cell and an approximate sample height of 100 mm. The experimental set allows to apply a pressure to the pore water up to 500 kPa. Figure 2 shows a schematic of the oedometric equipment. Water pressure is controlled by means of air pressure applying on the water surface. Interstitial pressure and applied water pressure is measured by two pore pressure transducers in the base of cell. The LVDT measures the displacement of the upper stainless steel loading plate in direct contact with sample. The press is capable of applying a vertical stress of 25 MPa.

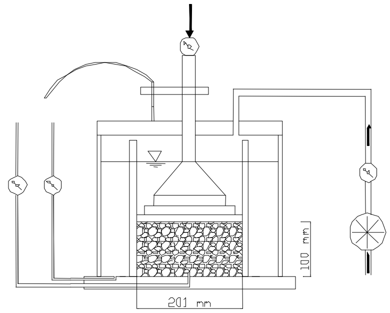

Figure 2. Scheme of the axial oedometric equipment

Prior to testing, the crushed rock was poured manually into the oedometric cell. The stainless steel loading plate is placed atop the sample. Sample compaction was carried out by means of a vibration table for a period of 60 seconds.

Rate of displacement of the bottom plate was the same in all tests and was equal to 1.16 µm/sec.

The amount of particle breakage was estimated from grain size analyses performed before and after each test.

In the flooded tests, water entered from the base of cell with a very low velocity. This type of flooding ensures rock pore wetting. The water level is constant in the whole flooded test with/without applied water pressure. This water level is shown in Figure 2.

3 GRAIN BREAKAGE

The particles of rockfill may be different from each other and the individual grains themselves may be composed of several minerals having dissimilar mechanical properties. The rock particles are generally brittle and have a compressive strength that is four or more times greater than their tensile strength. The grain may also have fissures and voids and be affected by weathering. These facts point out the degree of complexity that is involved in the process of breakage, taking in consideration the nature of materials. Stresses in a granular mass are transmitted through forces acting on limited areas (contacts) of grain surface. Furthermore, the statistical character of the contact forces plus the irregular geometry of the grain structure and of the contact surfaces, make it impossible to predict the state of stress inside the particles in a deterministic manner. It is the reason that the grain breakage is measured by sieves analysis. Grain size analysis gives a quantitative value of the grain breakage without consideration of historical stress that a grain is submitted before.

3.1 Quantification method

One of the most conspicuous phenomena observed in rockfill masses when stressed is the fragmentation of the component grains. Particle breakage changes the grain size distribution and appreciably affects the deformation characteristic of the materials. It may also influence the shear strength. The concepts and formulas presented in following were used by Marsal (1973) as the basis for studying the factors controlling particle breakage and for deriving a procedure to evaluate the amount of grain breakage due to change in the state of stress.

The gradation of a granular material changes during the loading process due to breakage of particles. The degree of grain breakage depends mainly on the gradation, the crushing strength of the grains, and the stress level. The results of an oedometric test on the crushed granite from Québec will be used to define a quantitative measure of grain breakage. The initial and final grain size curves are shown in the Figure 3a, where W_{ki} and W_{kf} are the weights of kth fraction before and after testing respectively, expressed as a percent of total weight of sample. The differences ΔW_k between the percentages of the total sample contained in each grain size fraction before end after the test is plotted versus the opening of the upper sieve corresponding to that fraction (Figure 3b). The algebraic sum of ΔW_k must be zero. A parameter B_g equal to the sum of the positive ΔW_k, expressed in percent is selected as a measure of grain breakage. Values of B_g are the percentage by weight of the solid phase that has undergone breakage. In the following ''grain breakage'' refers to the value of B_g in each test.

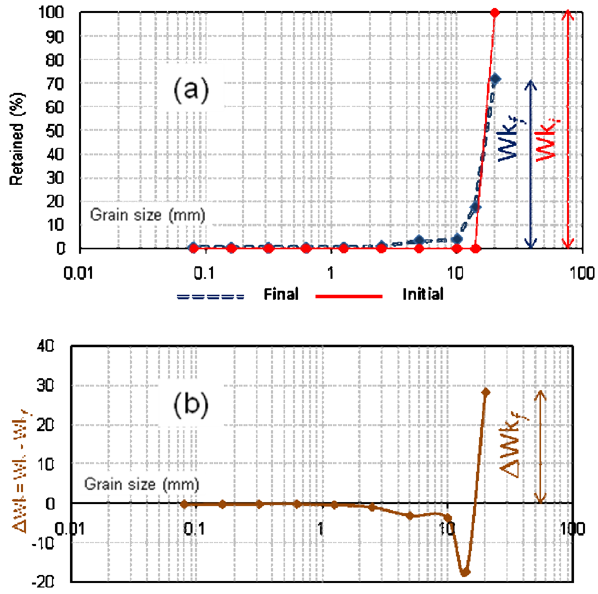

Figure 3. a) Initial and final grain size distribution b) Variation of the grain size distribution produced by particle breakage.

4 TEST RESULTS

Five Series of one dimensional compression tests were performed to investigate the factors influencing the settlements of uniform crushed aggregates. Each test Series consisted of four compression tests with different conditions:

- 1. Air-dry sample;
- 2. Air dry sample flooded under atmospheric pressure;
- 3. Air dry sample flooded under atmospheric pressure and subjected to a pore water pressure of 100 kPa;
- 4. Air dry sample flooded under atmospheric pressure and subjected to a pore water pressure of 200 kPa;

Particle diameter of specimens in Series 1, 2 and 3 varied between 20 mm and 28 mm while for test Series 4, particle diameter varied between 28 mm and 38 mm and between 38 mm and 56 mm for test Series 5.

In test Series 1, 4 and 5 the maximum axial force was 100 kN while in test Series 2 and 3, it was respectively 50 kN and 66 kN as summarized by Table 1.

Table 1. Summary of test conditions

Series no.	Grain sizes (mm)	Max vertical load (kN)
1	20-28	100
2	20-28	50
3	20-28	66
4	28-38	100
5	38-56	100

A granitic aggregate from the Quebec region (Sablière Drapeau), approved for granular base course, was selected for this study. The aggregates contain about 66% granitic gneiss, 24% biotite, and 9% hornblende. The density of solid particles larger than 5 mm is 2.69, and that of particles smaller than 5 mm is 2.70 (Konrad and Lemieux 2005).

5 RESULTS

5.1 Typical test

The results obtained from the first set of experiments are shown in Figure 4. As anticipated, vertical deformations were larger for test conditions 2 to 4 when compared to the air-dry test (condition 1). Moreover, it appears that for low stresses, there is a significant increase in the vertical strain when water pressure increases. For higher stresses, however, the trend reverses.

Figure 5 shows the grain size analysis after each test of the first set of compression tests.

Grain breakage occurred in all the tests for all conditions tested. Grain breakage was maximum for the flooded condition under atmospheric condition. Increase in the water pressure diminished the amount of grain breakage.

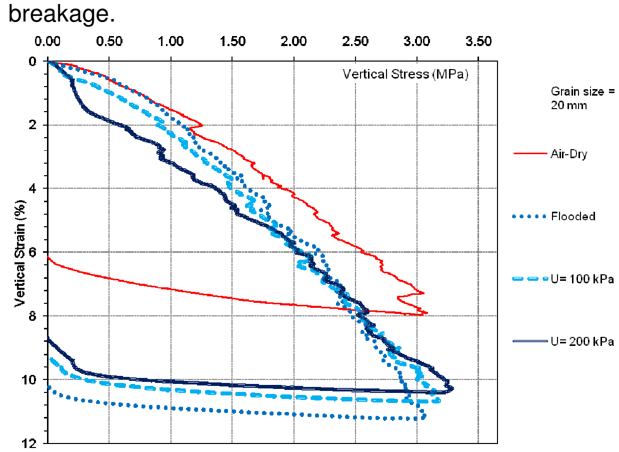

Figure 4. Stress-stress curve in series 1 (refrence to Table 1).

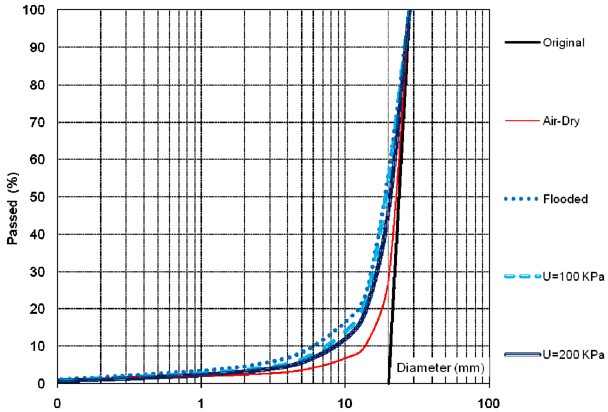

Figure 5. Grain size curve in series 1 (refrence to Table 1).

5.2 Influence of grain size

Figure 6 illustrates the amount of grain breakage for test Series 1, 2 and 3. The difference between each test was the grain size which varied on average from 24 mm to 47 mm. Grain breakage increases with increasing grain size. It was also noted that the test under condition 3 (air-dry, flooded and submitted to 100 kPa water pressure) have more variance than those under a water pressure of 200 kPa.

Figure 7 shows the grain size effect on the vertical strain. It can be seen that the vertical strain increases with increasing grain size for all the test conditions. Again, there seems to be more variability for test condition 3.

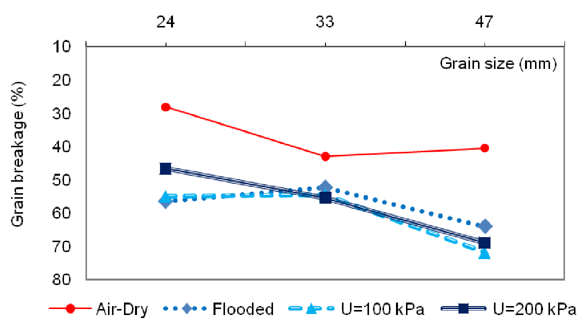

Figure 6. Grain size effect on grain breakage

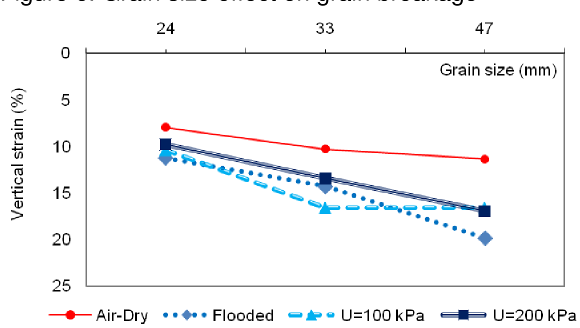

Figure 7. Grain size effect on vertical strain

5.3 Influence of stress level

Three test Series (1, 4 and 5) were realised to investigate the influence of stress level on the grain breakage and vertical strain. In these tests, the average grain size was 24 mm. Applied loads were respectively 100, 66 and 50 kN, which, in turn, resulted in nominal vertical stresses of 3, 2 and 1.55 MPa. As anticipated, increasing stress levels results in more grain breakage as shown in Figure 8.

Figure 9 shows the amount of vertical strain at different levels of applied stress. As expected, the vertical strain is a function of the applied stress. In all tests the vertical strain varies linearly with the vertical stress excepted in the tests conducted with an applied pore water pressure of 100 kPa.

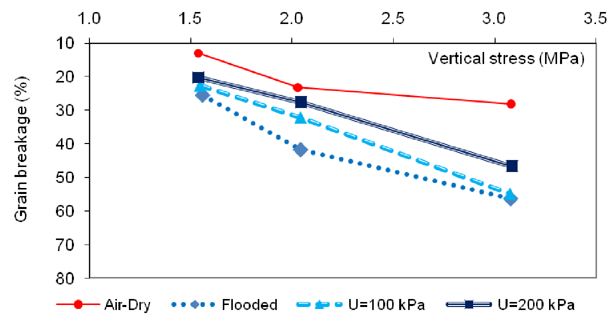

Figure 8. Influence of stress level on grain breakage

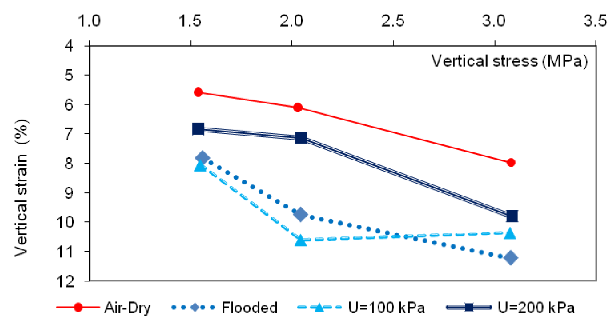

Figure 9. Vertical strain in different vertical stress level

6 CONCLUSION

In the present paper, the settlement and the grain breakage of crushed rock particles was investigated for different conditions associated with pore water, i.e air dry, saturated, saturated with a pore water pressure of 100 and 200 kPa, respectively.

An oedometer cell was used to obtain data on a granitic aggregate from the Quebec region (Sablière Drapeau).

It was established that the amount of grain breakage was linearly related to stress level and was strongly influenced by the presence of pore water. Maximum grain breakage, however, occurred for the condition where the samples were flooded under atmospheric pressure. Increasing the pore water pressure resulted in less grain breakage. The smallest amount of grain breakage occurred for air-dry samples.

Vertical strain can be directly related to the amount of grain breakage. Grain breakage increases with increasing grain size.

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