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Reducing water effects on coarse granular aggregates

Réduction des effets de l'eau sur agrégats granulaires grossiers

A. Ramon
Division of Geotechnical Engineering and Geoscience of the Department of Civil and Environmental Engineering, Universitat Politecnica de Catalunya (UPC) & International Centre for Numerical Methods in Engineering (CIMNE), Barcelona, Spain

M. Montserrat, E.E. Alonso, and Enrique Romero
Division of Geotechnical Engineering and Geoscience of the Department of Civil and Environmental Engineering/Universitat Politecnica de Catalunya (UPC), Barcelona, Spain

ABSTRACT: Rockfill embankments, rockfill dams and ballast beds experience long term compression deformations under constant loading as well as collapse deformations when relative humidity (RH) increases. Particle breakage is at the origin of post construction deformations of infrastructures made of gravels and rockfill. Prevailing RH, inter-particle contact loads and material toughness control particle breakage.
The aim of the investigation described in the paper was to explore a treatment for granular media that allows the reduction of post construction deformations of transportation infrastructures. The objective was to decrease or eliminate the influence of relative humidity in particle breakage.
The fundamentals of the hydrophobicity (repellence to water) of surfaces have been investigated with the aim of developing a stable hydrophobic coating treatment at laboratory scale. The effectiveness of the treatment has been studied experimentally by means of large diameter oedometric and uniaxial compression tests. Samples of gravel treated with hydrophobic coatings and non-treated gravel were tested under different conditions of relative humidity.
The Sessile Drop Method allowed the verification of the hydrophobicity of the tested rockfill particles after the application of the water-repellent treatment. Uniaxial compression tests on individual particles showed that the water-repellent treated particles achieve the same uniaxial compression strength when tested under wet or dry conditions. The samples prepared with hydrophobic-treated particles underwent lower compressibility than the samples built with non-treated particles in large diameter oedometric tests.

RÉSUMÉ: Les remblais d'enrochement, les barrages d'enrochement et les lits de ballast connaissent des déformations de compression à long terme sous charge constante ainsi que des déformations par effondrement lorsque l'humidité relative (HR) augmente. La rupture des particules est à l'origine des déformations post-construction des infrastructures en graviers et en enrochement. L'humidité relative, les charges de contact entre particules et la ténacité du matériau permettent de contrôler la rupture des particules.
Le but de l'investigation décrite dans le document était d'explorer un traitement des matériaux granulaires permettant de réduire les déformations des infrastructures de transport après la construction. L'objectif était de réduire ou d'éliminer l'influence de l'humidité relative dans la fragmentation des particules.
Les fondements de l'hydrophobicité (répulsion à l'eau) des surfaces ont été étudiés dans le but de développer un traitement d'enrobement hydrophobe stable à l'échelle du laboratoire. L'efficacité du traitement a été étudiée expérimentalement au moyen d'essais oédométriques de grand diamètre et essais de compression uniaxiale. Des échantillons de graviers traités avec des recouvrements hydrophobes et de graviers non traités ont été testés dans différentes conditions d'humidité relative.

La méthode des gouttes sessiles a permis de vérifier le caractère hydrophobe des particules d'enrochement testées après l'application du traitement hydrophobe. Les tests de compression uniaxiale sur des particules individuelles ont montré que les particules traitées hydrophobes atteignent la même résistance à la compression uniaxiale lorsqu'elles sont testées dans des conditions humides ou sèches. Les échantillons préparés avec des particules traitées hydrophobes ont subi des déformations de compression moins importantes que celles des échantillons avec particules non traitées lors d'essais oedométriques de grand diamètre.

Keywords: Rockfill; gravel; compressibility; relative humidity; hydrofobicity

1 INTRODUCTION

Civil structures made of coarse granular aggregates (rockfill and gravel), i.e. rockfill dams, road and railway embankments and also railway ballast layers, experience collapse and long term post construction deformations (Marsal 1973; Naylor et al., 1997; Oldecop and Alonso, 2001). Field post construction deformations are controlled, to a large extent, by the relative humidity prevailing in the atmosphere. These phenomena are explained by the breakage of particles. Experimental investigation on the behaviour of granular structures by means of oedometer and triaxial tests demonstrate that deformations induced by sample loading and saturation were the result of particle breakage (Marsal, 1973; Ramon et al., 2008, Alonso et al., 2016). The concentrated loads applied to the particle contacts are high and are capable of breaking the individual rock particles. The breakage is controlled by the stress level, the thoughness of the material and the action of water.

Breakage is explained by the progress of existing fissures in the rock particle. Under the perspective of the linear elastic fracture mechanics (LEFM) the velocity of the opening of fissures in time is controled by the relative humidity at the tip of the fissure and by the toughness of the material. Therefore, a high relative humidity in the air filling the pores of rockfill and gravel favours the rapid propagation of fissures and the breakage of particles.

Oldecop and Alonso (2001) carried out a series of oedometric tests with a continued control of the relative humidity of the sample. Their results showed that the relative humidity existing in the pores of the material controls the development of collapse strains. It is not necessary to saturate the sample to induce a collapse deformation (Figure 1). Oldecop and Alonso (2001 and 2003) proposed an strain hardening elastoplastic constitutive model for rockfill that introduced the concepts of particle breakage and the influence of the presence of water on its mechanical behaviour.

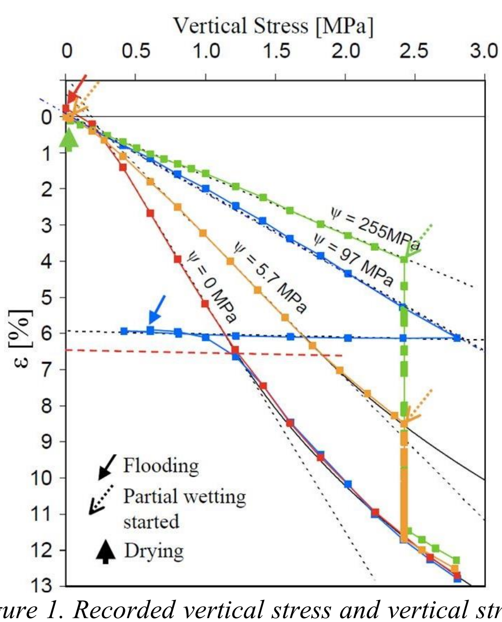


Figure 1. Recorded vertical stress and vertical strain in oedometric tests under different suctions (Oldecop and Alonso, 2003)

The model formulation is based on the hypothesis that two different mechanisms originate plastic deformation: the instantaneous deformation mechanism (IDM) and the time-dependent deformation mechanism (TDM). The model considers that the instantaneous deformations are present under any stress level and are independent of the presence of water. They occur under dry conditions (at a certain relative humidity). However, the time-dependent deformations appear beyond a stress threshold that defines the onset of particle breakage, the clastic yield stress, and water has an important role on its development.

The present investigation focuses on the study of the effectiveness of a procedure to decrease the influence of relative humidity on particle breakage in coarse granular materials and its effects on the behaviour of granular structures. There are certain chemical components that, when applied on a surface, modify the energy of water in contact with the surface and provide repellence to water (hydrophobicity) to the surfaces coated with these products. The fundamentals of the hydrophobicity of surfaces were investigated with the aim of developing a stable hydrophobic coating treatment at laboratory scale, also applicable to rockfill embankments and ballast layers. Since rockfill and gravel structures are made up of rock particles with maximum sizes between 0.5-1.5 meters and 5-6 cm respectively, scaled tests simulating the behaviour of particle contacts and the granular structure were selected to investigate the effectiveness of the procedure. A program of oedometric and uniaxial compression tests on samples of gravel treated with hydrophobic coatings and non-treated gravel was carried out under different conditions of relative humidity. Test results allowed the study of the effect of the hydrophobic treatment.

This paper starts with a brief description of the hydrophobicity fundamentals. Then the experimental investigation, the testing procedures and results are described and discussed. The conclusions are highlighted in the last section of this paper.

2 HYDROPHOBICITY FUNDAMENTALS

The contact angle is the basic parameter that measures the wetability of a solid surface. This is the angle between the plane of the solid surface and the tangent to the meniscus of a liquid in contact with a solid surface at equilibrium (Figure 2). The Young equation, which describes the equilibrium of the liquid-gas interface in contact with a solid surface, accounts for the intermolecular forces of the liquid, solid and gas phases and is written as follows:

$$\cos\theta_Y = \frac{\gamma_{SG}-\gamma_{SL}}{\gamma_{LG}} \quad (1)$$

where θ_Y is the equilibrium contact angle, γ_{SG} is the solid-gas interfacial energy, γ_{SL} is the solid-liquid interfacial energy and γ_{LG} is the liquid-gas interfacial energy (surface tension).

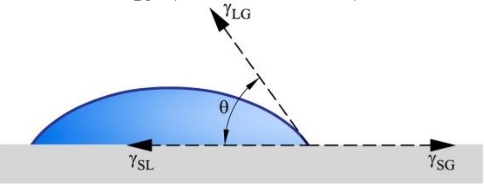


Figure 2. Representation of the contact angle of a liquid-gas interface with a solid surface

The value of the contact angle permits to classify the solid surfaces as hydrophobic or hydrophilic. An hydrophilic surface is a surface that can be wet and, therefore, a drop of water in contact with the surface will develop a contact angle smaller than 90º. On the contrary, an hydrophobic surface is not wettable, the surface “repels“ the liquid and the contact angle is larger than 90º.

According to Young equation the equilibrium contact angle is intrinsic of the liquid-solid-gas system at a given pressure and temperature.

However, a contact angle hysteresis exists around the equilibrium contact angle when water is added or removed from the system. In addition, the roughness of the surface can influence the contact angle (Nosonovsky and Brushan, 2009) and is capable of transforming a hydrophilic surface into a hydrophobic surface or to increase the initial hydrophobicity of a hydrophobic surface.

An artificial hydrophobic surface can be achieved through two techniques: the provision of roughness or the lowering of the surface energy by coating the surface by a material with low surface energy. The most used hydrophobic agents are silane or siloxane chemicals. The literature reports investigations on the achievement of artificial hydrophobic soils in order to obtain stable impervious fills and barriers due to its hydrophobic behaviour (Lourenço et al. 2015). This contribution describes the application of hydrophobic treatments in silty and clayey soils and in sands. The most common chemical compounds used in soils are based on Dimethyldiclorosilane (DMDCS) and n-octytrietlhoxysilane (Lourenço et al., 2015; Ng and Lourenço, 2015).

3 EXPERIMENTAL INVESTIGATION

3.1 Testing procedure

The tested material was a gravel made up of quarzitic slate of Cambrian age recovered from an outcrop of the Pancrudo River (Spain).

The size of the tested gravel particles ranged from 20 to 30 mm. The experimental work involved the testing of gravel treated with the chemical compound DMDCS, to acquire hydrophobicity characteristics, and testing also natural (non-treated) gravel through a series of uniaxial compression tests and oedometer tests. Both types of tests were conducted at different Relative Humidity (RH) conditions: the samples were tested at dry conditions, corresponding to the environmental laboratory conditions (50-65% RH and 25ºC), and under saturated conditions.

The uniaxial compression tests were conducted on individual particles by means of a special equipment that permits the control of the RH during the test. An increasing stress was applied during the test until the detection of the particle breakage. The tests were conducted on particles with similar shape to minimize the geometry effects. Figure 3 shows the initial geometry of the gravel particles selected for the uniaxial tests.

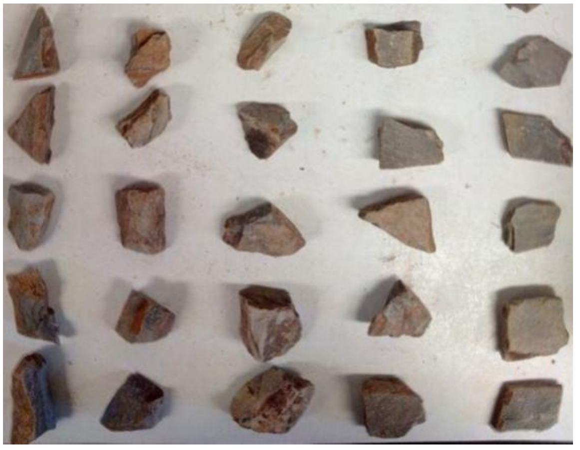


Figure 3. Gravel particles before testing by means of uniaxial tests

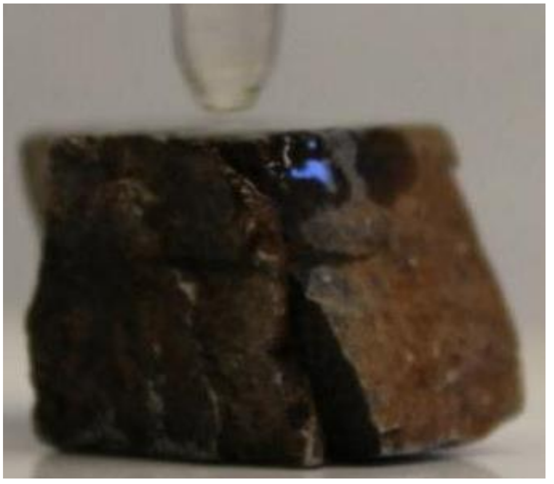
Large oedometric tests were carried out on gravel samples by means of Rowe oedometric cells 15 cm in diameter. Maximum stresses of 1.7 and 2 MPa were applied following dry and saturated loading and unloading paths. Stress was applied along increasing loading steps. Each loading step lasted 24 hours. A saturation of the sample was induced at the end of the loading path conducted at dry conditions. Unloading under dry conditions was also carried out in some samples to investigate the effect of sample saturation on particle breakage.

3.2 Test results. Description and discussion

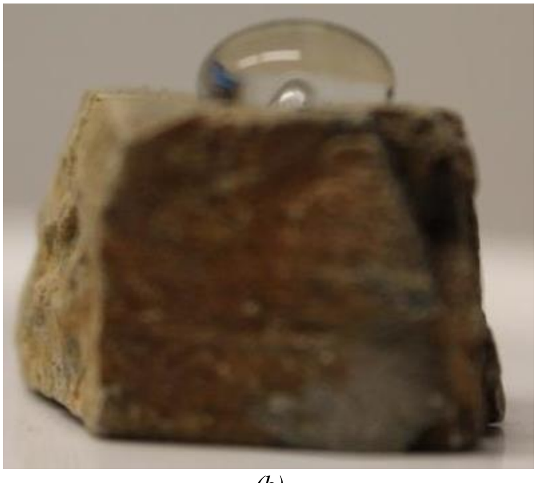
The hydrophobic efficiency of the coating treatment based on DMDCS was investigated by measuring the degree of hydrophobicity of the gravel before and after the hydrophobic treatment. The wettability of the surface of the gravel particles was investigated by means of a procedure similar to the Sessile Drop Method. First, water drops were deposited on flat surfaces of the particle gravel with a pipette. Then, the static contact angle defined between the flat surface of the particle and the tangent to the meniscus of the drop of water was directly measured (Figure 4). This analysis was done to the same particles before and after the application of the treatment. Figure 5 shows the shape of a water drop on the surface of a gravel particle before (Figure 5a) and after (Figure 5b) the hydrophobic treatment. Water drop deposited on non-treated surfaces achieved a film shape on the surface. A complete wettability with a contact angle of 0º was assumed for the natural gravel. On the other hand, water on all treated surfaces showed a well-defined drop shape (Figure 4 and 5b) with average contact angles close to 100º.

Figure 4. Measurement of the contact angles of a drop on a hydrophobic treated surface

Uniaxial tests on individual particles were conducted with a continuous measurement of the uniaxial compressive load in time during the loading of the particles. Figure 6 shows the evolution of the recorded vertical load with the imposed loading displacement in uniaxial tests performed under saturated conditions. The test results on treated and non-treated gravel particles are compared in the figure. The load magnitude measured immediately prior to recording a decrease of load was assumed to correspond to the uniaxial compressive failure load.



(a)



(b)

Figure 5. Shape of a water drop on the same particle surface: a) without tratment, b) with the hydrophobic treatment

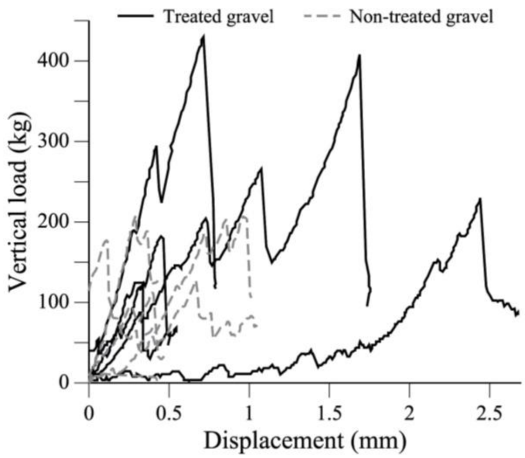


Figure 6. Evolution of measured vertical load and imposed displacement during ten uniaxial loading of individual gravel particles

The frequency distributions of the compressive failure load recorded in uniaxial tests performed under saturated conditions on treated and non-treated gravel particles are plotted in Figure 7. Coated particles exhibited higher uniaxial compressive failure load. Values up to 920 kg were recorded in tests performed on treated particles. On the contrary, the maximum values of compressive failure load measured in tests on non-treated gravel stayed around 270 kg. The uniaxial compressive failure strength of each particle was calculated as the ratio between the uniaxial compressive failure load and the squared diameter of the particle. The tests carried out under saturated conditions showed that the non-treated particles had a lower failure strength with maximum values close to 110kg/cm^2 (11 MPa). The treated particles exhibited similar compressive failure strength when tested under dry or saturated conditions, with values ranging from 40 to 450 kg/cm^2 (4 to 45 MPa) .

The different strength behaviour between treated and non-treated particles under saturated conditions is explained (i) by the effect of water on the acceleration of fracture propagation and (ii) by the superficial protection against wetting provided by the hydrophobic treatment. The test results showed that the hydrophobic treatment of the particle surfaces is capable of protecting the tip of the existing fractures from the increase in relative humidity and, therefore, from the progression of the fissure. Once the region of the particle in contact with the loading plates is crushed, due to the concentrated high loads applied, the protection disappears at those areas and the new fissures will progress with a speed accordingly with the prevailing relative humidity. This behaviour results in a higher uniaxial compressive failure strength.

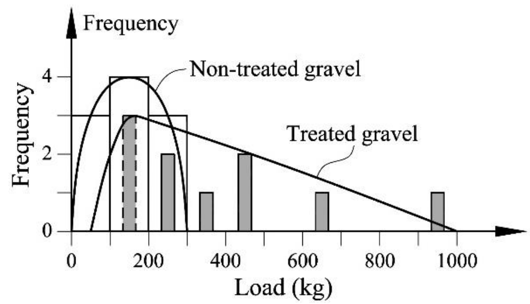


Figure 7. Distribution of the compressive failure load frequency in saturated uniaxial tests

Figure 8 shows the measured vertical strain against load for two oedometer tests carried out under saturated conditions on treated and non-treated gravel. The plotted strain values correspond to the measured vertical strains after 24 hours of application of each loading increment. Stress-strain curves show the typical different stages of the compression of rockfill. Initially, during the clastic plastification, gravel samples deform due to particle breakage following a normal consolidation line, which is linear in natural scale. At higher stresses, a clastic hardening occurs and strain evolves linearly with increasing stress at logarithmic scale.

The comparison of the behaviour of the gravel treated with a hydrophobic chemical compound and the non-treated gravel under saturated conditions shows that compressibility under saturated conditions decreased on treated gravel. This reduction on strain resulted in to a decrease of the accumulated vertical strain at the end of the test of 2.4% (Figure 8).

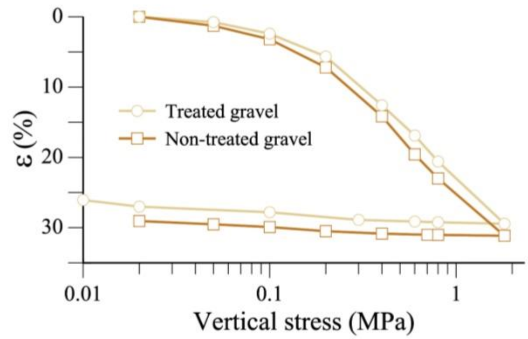


Figure 8. Measured vertical strains against vertical stress during saturated oedometric tests

Oedometer tests allowed also the analysis of the long-term effect of the hydrophobic coating. The evolution of strains in time under constant load is shown in Figure 9 for two tests carried out on treated and non-treated gravel samples under saturated conditions. Each curve corresponds to the deformation developed under constant load for the loading steps applied to the samples. The comparison shows that the hydrophobic coating reduced the deformation of gravel samples under saturated oedometric conditions. Treated samples developed smaller deformations in time for all loading steps applied. A rapid increase of vertical deformation was recorded after the application of load followed by a linear long-term evolution of strains over time in logarithmic scale. This behaviour was also observed in other rockfill compressibility studies (Marsal, 1973, Nobari and Duncan, 1972, Oldecop and Alonso, 2001, Ramon et al., 2008).

The detailed observation of the tested gravel samples after oedometer tests showed that particle breakage had occurred during oedometer tests and that fissures cross the area close to the particle contacts. The majority of the particles presented diametral fractures and fissures. Calculated Marsal and Hardin indices after the tests and the final fractal dimension verified the development of particle breakage during the oedometric tests. Figure 10 represents the original grain size distribution of the tested gravel and the grain size distributions at the end of saturated oedometer tests carried out on treated and non-treated gravel samples. Particle breakage was higher on samples without hydrophobic treatment. Particle breakage observed at the end of the tests depends on the dry or saturated characteristics of the loading path. Tests resulted in lower particle breakage when the samples were saturated at the beginning of the test.

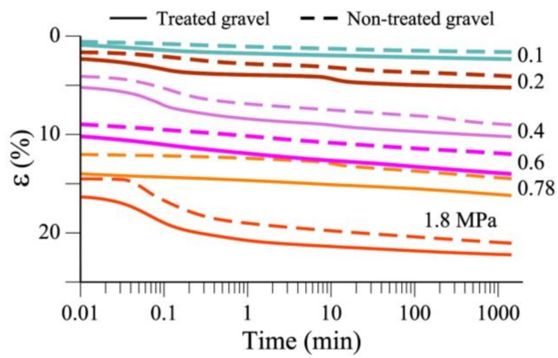


Figure 9. Evolution of vertical strains over time on non-treated and treated saturated gravel samples under constant load for each loading step applied

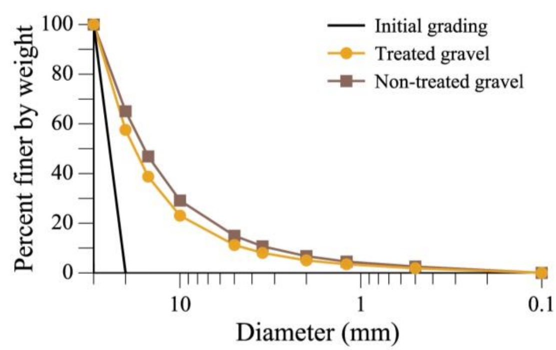


Figure 10. Original grading and grading at the end of saturated oedometer tests performed on natural and treated gravel samples

4 CONCLUSIONS

A procedure to reduce the long-term deformations in coarse granular structures has been investigated. Deformations in these structures occur in time as a result of particle breakage. The idea followed in this paper has been to protect granular particles against the effect that relative humidity at inter-particle pores has on the progression of fissures and, therefore, on particle breakage. The effect of this protection on granular structure compressibility has been studied. A coating treatment based on the chemical compound Dimethyldiclorosilane was chosen to build water repellency at the surface of gravel particles. An experimental investigation on uniform treated and non-treated gravel samples was carried out.

The direct measurement of contact angles of water drops on the treated surfaces has indicated that a high hydrophobicity was achieved at the particle surface after the treatment.

Uniaxial tests on individual particles have shown that the coating treatment was effective for the reduction of the initial particle breakage under saturated conditions. In addition, the hydrophobic treatment has reduced the compressibility under saturated conditions in gravel samples tested in oedometric tests.

The amount of particle breakage after oedometric tests has been lower for the treated gravel samples.

5 ACKNOWLEDGEMENTS

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