

THE INFLUENCE OF CLAY-LIKE MATERIALS PLASTICITY USED AS INFILLS, ON JOINTED ROCKS MECHANICAL BEHAVIOR

Ngaha Tiedeu William ^{1,2}, *Jiang Deyi ¹, Chen Jie ¹, *Fan Jinyang ¹

¹ School of Resources and Environmental Sciences, Chongqing University, Chongqing 400044 China;

² National Advanced School of Engineering, University of Yaoundé I, Yaoundé 8390 Cameroon

*Corresponding Author, Received: 04 March 2019, Revised: 01 April 2019, Accepted: 30 April 2019

ABSTRACT: The Rock mass is often described as an anisotropic material with several discontinuities within its structure ranging from joints, bedding plans to faulting. In the present study, the effects of infills plasticity on rock mass behavior during failure were investigated. Thus, a series of experiments have been conducted on both soils and cement blocks reconstituted to reflect jointed rock behavior. Different soil materials (obtained by mixing clay and sand) were subject to the cone penetration test and the unconsolidated undrained triaxial test to determine their plasticity index and their unconfined compressive strength. Then, several jointed blocks using the aforementioned soil materials as infill were subject to a uniaxial compression test to assess their maximum stress and investigate their deformation and failure mode. Results showed that stiffer infills would induce a more brittle behavior in the jointed rock while softer infills would instead favor rock deformation and a sharp decrease of its strength. It was also observed that both infill' cross-section and thickness will affect the rock resistance but its deformation will largely be influenced by the later. In the end, some law equations were proposed to draw the mathematical relationship between the jointed rock maximum stress, its deformation at failure and the infill plasticity.

Keywords: Rock strength, Rock deformation, Failure mode, Infill plasticity.

1. INTRODUCTION

Rock masses, in their natural state, are generally characterized by a variety of discontinuities present on their structure. Those discontinuities are often classified into four types including joints, bedding plans, folds and faults. Because of the presence of those discontinuities along with other heterogeneous properties, the rock resistance can largely be affected. For practical operations such as underground excavations in mining and construction projects, these structural defaults would have a more critical influence. Among all discontinuities, joints are the most common, especially in tropical regions [1, 2] and they can be open (with or without infilling) or healed (close).

Years of alteration and weathering can often bring some fine sediments into the rock mass' open fracture and therefore affect its overall resistance to failure. These fine sediments generally made of clay, sand or silt constitute what is known as rock infill. With the presence of these infills, the strength of the rock joint will be affected and both the cohesion and the friction angle at the interface will vary according to the infill properties [3, 4].

One important property of the rock infill is its compressibility, which along with cohesion and consistency can be characterized by the plasticity index. Therefore, the higher the clay content in an

infill, the more cohesive it will behave. This various level of plasticity can influence the infill strength, its consistency as well as its permeability. As a result of that, the discontinuity resistance to failure as well as the overall rock strength will be affected.

In this paper, a series of experiments on both soil and rock specimens were conducted. Four different types of soils, presenting different values of plasticity ranging from 23.0 to 9.0 were considered and cylindrical mortar blocks were used to reconstitute rock specimens of moderate strength for laboratory tests. Specifically, soil materials were subject to two experimental tests including the cone penetration test to access soil plasticity and the triaxial compression test to determine the soil unconfined compressive strength. Afterward, jointed rocks were reconstituted in the laboratory using soil material as infills and cement blocks as the intact rock material. The specimens were then subject to a uniaxial compression test to study the relationship between infills plasticity and the rock mass behavior during failure.

2. TEST MATERIAL

The preparation of different laboratory tests has required the use of different materials for reconstituting both the jointed rock and the infill. For making jointed rocks, mortar made from

Portland cement 42.5 and river sand was used. Besides, clayed materials of different plasticity served as infills. The different ranges of plasticity were obtained by mixing pure clay with different quantities of fine sand.

2.1 Cement

According to the cement naming standard, hydraulic minerals contained in cement are the principal element used for defining a type of cement. Based on that classification, there are portland cement, aluminate cement, sulphate cement and sulpho-aluminate cement, and phosphate cement[5].

Among many varieties of cement, the one commonly used is Portland cement (including ordinary Portland cement, Portland blast furnace cement, Portland pozzolana cement, Portland fly-ash cement, and composite Portland cement)[6]. The strength grades for the ordinary Portland cement are 32.5, 32.5 R, 42.5, 42.5 R, 52.5, 52.5 R. In this study, the chosen strength was 42.5.

2.2 Clay

Clay is a finely grained material from natural rock and soil that consist of minerals such as hydrous aluminum and little traces of quartz, metal oxides and organic matter. The major content of geologic clay deposits is phyllosilicate minerals, which contain variable amounts of water found in its mineral structure[7, 8]. The clay material used for the present study comes from the small city of Jingdezhen, Jiang Xi province, South East China.

2.3 Sand

Two different kind of sands were used for preparing the experimental specimens: river sand and silty (fine) sand. The river sand was used to prepare the mortar whereas the silty sand was used to modify the plasticity of the pure clay. By adding various amount of silty sand to the original clay, the plasticity of the resulting material was changed accordingly.

3. EXPERIMENTAL DESIGN

3.1 General Procedure

For assessing the influence of infills properties, especially plasticity, on the overall rock strength, reconstituted specimens of jointed rock were subject to various laboratory tests.

The reconstituted jointed rocks were made of cement blocks having an aperture at its center filled with soil material of various size and composition.

To form the clay material, both kaolinite and silty sand were used. The five varieties of infills

used in this experiment were:

- Infills only made of kaolinite that is 100% clay
- Infills made of 80% kaolinite and 20% silty sand
- Infills made of 60% kaolinite and 40% silty sand
- Infills made of 40% kaolinite and 60% silty sand
- Infills made of 20% kaolinite and 80% silty sand

For assessing the mechanical properties of different infills, some laboratory tests were conducted including the cone penetration test to determine the infill plasticity and the Unconsolidated Undrained triaxial compression test to determine the material's unconfined compressive strength.

The following step consisted of preparing the cement blocks with a layer of soil material incorporated as infills. The whole system served to simulate the behavior of jointed rocks during laboratory tests. In the end, the jointed cement blocks (cement blocks with handmade open cracks filled with clayed material) were subjected to uniaxial compression tests.

3.2 Experimental Tests on Clays Materials

As presented above, the clay material used in the experimental tests was made of kaolinite and silty sand mixed at various proportions. The studied properties were the plasticity obtained using the cone penetration test and the unconfined compressive strength using the triaxial test.

3.2.1 Plasticity determination

Infill plasticity was determined for four different varieties of clayed material, with various proportions of clay namely 100%, 80%, 60% and 40%. The cone penetration test was used to access the material's plasticity.

Firstly, specific proportions of fine sand and kaolinite were prepared and then mixed with water. The quantity of added water was a function of the targeted depth of penetration of the cone. In our case, the selected depths were 3mm, 7mm and 15mm.

After that, the test was started by activating the penetrometer and for every depth, a small amount of material was taken apart for determining the water content. Using both the cone depth and the obtained water content served to draw a linear relationship curve between the two parameters.

3.2.2 Unconfined compressive strength of soil

This parameter was determined using the triaxial test apparatus. The four types of soil materials were prepared at a specific density and

water content. Based on field observations, the selected density and moisture for the unconsolidated-undrained triaxial test were 17 KN/m³ and 15% respectively. The compression test was conducted at a constant strain speed ratio of 0.3 mm/min. Likewise, Mohr circles were drawn based on results for three values of the compressive force which were 200 KPa, 400 KPa and 600 KPa. This served to compute the material friction angle ϕ and undrained shear strength C_u .

From this, the unconfined compression strength q_u was determined using the following formula:

$$q_u = 2C_u \quad (1)$$

3.3 Experimental Tests on Jointed Blocks

The last phase of our experimental study was to conduct uniaxial compression tests on jointed cement blocks. The jointed cement blocks were made of cement, sand and water mixed at a proportion of 2:3:1 with the addition of a semi-circular compacted soil layer at the middle of the block (Fig.1).

The test was conducted using a standard testing system (Fig. 2) to determine the block compressive strength based on the quality and the size of the soil material inserted at its center. The standard specimen size was 100mm length x 50mm diameter[9]. For the various types of soil materials used as infill, there were four different configurations. The first two of them were a semicircular soil layer (covering half of the cement block's cross section) with two different thicknesses (5mm and 10mm). The second two kinds were a quarter circular layer (covering 25% of the block's cross section), here too with 5mm thickness in one case and 10mm in the other.

Before the uniaxial compression test was performed on jointed cement blocks, the specimens were prepared by mixing cement, sand, water and adding a soil layer at the middle. Then, they were cured for 28 days at a constant room temperature of about 15°C. After this period, the specimens were polished for smooth and perfectly planar surfaces to ensure accurate compression test results. The height and diameter of each specimen were measured and saved for future computations.



Fig.1: Specimen during the 28days cure period

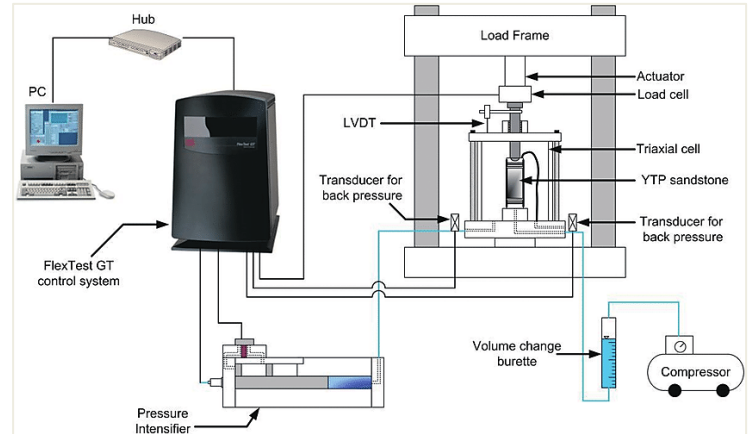


Fig.2: Test setup for cement blocks compression[10]

4. RESULTS AND DISCUSSIONS

Conducting all the three experimental tests was important to assess both the soil properties that are used as infills and their influence on the overall jointed rock behavior during failure. The characteristics to investigate regarding the soil material were its plasticity, its cohesion and its shear strength. Concerning jointed cement blocks, the studied parameters included the maximum stress at failure, the time duration before reaching the specimen failure, the specimen deformation trend throughout the compression process, the specimen compressive strength and finally the specimen mode of failure.

These different analyses helped to better understand how infills plasticity could trigger a more or less faster failure of the rock mass.

4.1 Cone Penetration Test

For a given soil type, the plasticity index was determined through a few steps. The first was to evaluate the cone depth for different soil saturation states. Then assess the soil water content for three specific depths that were 3mm, 7mm and 15mm. Having determined the different depths with their corresponding water content, the variation curves of the soil moisture versus the cone depth for the five soil compositions considered in this study were drawn. The results obtained showed that the last soil composition (20%clay+80%sand) was a sandy soil and therefore the plasticity index measurement was not applicable to it. For computing, the plasticity index, two specific values of the cone depth ($d_1=2.2\text{mm}$ and $d_2=20\text{mm}$) were considered along

with their respective water contents (w_1 and w_2). The plasticity index (PI) was given by the formula:

$$PI = (w_2 - w_1) \times 100 \quad (2)$$

The plastic limit test procedure has been conducted in accordance with the ASTM standards. Results after computation are as follows:

Table1: Different soil specimens' plasticity

Soil	100-0	80-20	60-40	40-60	20-80
PI	22.5	19.1	12.5	9.5	-

4.2 Triaxial Test on Soil Specimens

The variant of triaxial tests used in this study is the Unconsolidated Undrained (UU) triaxial tests as they are more suitable for clayed soils[11]. UU triaxial tests are useful for determining the soil strength parameters including the undrained cohesion C_u and the angle of internal friction ϕ_u . For saturated soils, the angle of internal friction is zero and the undrained shear strength is equal to the undrained cohesion.

Based on the Mohr-Coulomb failure criterion, soil materials failed due to the dual action of normal stress and shear stress. Therefore, there is a linear relationship between the shear strength (τ_f), the normal stress (σ) and the internal friction angle (ϕ), given by the following formula:

$$\tau_f = c + \sigma \tan \phi \quad (3)$$

Where c represents soil cohesion.

As mentioned earlier, working on saturated soils (as the pressure chamber was fully filled with water throughout the test), will imply $\tau_f = c$.

Based on Mohr diagrams and Eq.1, it was possible to determine the undrained shear strength C_u and the unconfined compression strength q_u as given in the following table.

Table2: Different soil specimens' strength

Specimen	100-0	80-20	60-40	40-60	20-80
C_u (kPa)	80.65	56.71	31.54	4.73	0
q_u (kPa)	161.3	113.4	63.08	9.46	0

4.3 Uniaxial Test on Jointed Cement Blocks

The jointed cement blocks used for those tests were representative of jointed rocks of moderate strength. The test conducted on about 30 specimens served to obtain some properties of the specimens including the maximum compressive strength, the deformation pattern and the failure mode.

In the following sections, a specific notation was used to refer to the different tested specimens. All specimens (S) will be represented under the notation S-X-Y-ei-Z%; where 'X' and 'Y' are respectively the proportion of clay and sand in the infill, 'e' the infill thickness ($e_1=5\text{mm}$, $e_2=10\text{mm}$) and Z the specimen' cross area covered by the infill (there were two cases, 25% and 50%).

4.3.1 Specimens' maximum stress and deformation

Uniaxial compression tests were conducted on cement blocks with infills of various composition and the following curves were drawn (Fig.3).

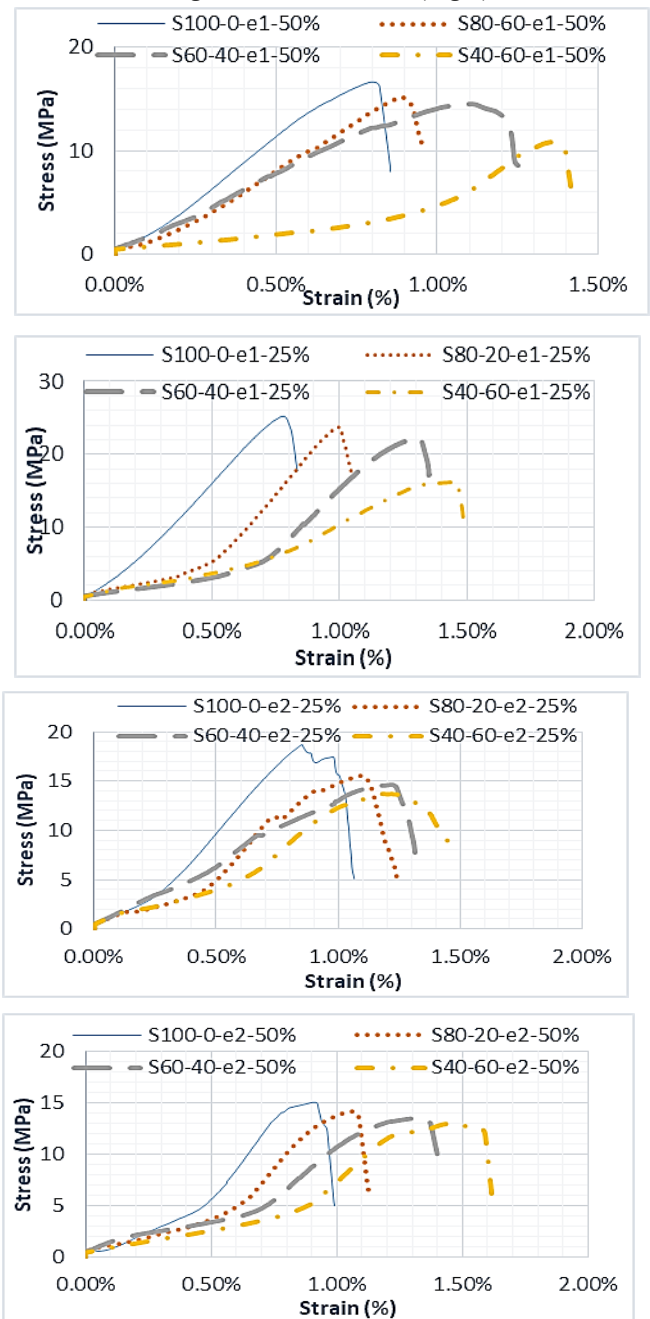


Fig.3: Curves of axial stress as a function of strain for various infill thickness and section

From the different diagrams presented above, it clearly appears that the specimen axial stress will decrease as the clay proportion in the infill decreases. Overall, it can be said that the presence of infill in the rock mass will affect its general strength but the infill consistency and plasticity will also play an important role. For instance, for specimens with infills of size $\epsilon 1-25\%$, the maximum stress will decrease from 25MPa (S-100-0) to about 15MPa (S-40-60). This is correlated to results obtained when assessing the soil undrained shear strength where it was found that the strength of Soil 100%-0% was almost 20 times higher than that of Soil 40%-60%. However, there is not a systematic linear relationship between the strength decrease in specimens and the strength decrease in the soil samples. That is because cement blocks have a much higher resistance to compression than soil and therefore the specimen failure behavior would, for a considerable part, depend on the cement blocks resistance. It is also worthwhile mentioning that the extent of strength decrease will also be influenced by the size (thickness and cross-area) of the infill as those parameters might affect the crack propagation behavior within the specimen.

Based on the diagrams above and experimental results, it can be inferred that specimens with highly plastic infills have a higher brittleness than specimens with infills composed of less clay. This can also be explained by the high consistency property of clay materials, which form solids bounds when dried and tend to deform less and break very fast under the effects of an external force. This means that when cracks reach the soil layer within the jointed rock structure, the deformation phase before the soil failure will be relatively short for highly clayed materials. When observing the curves above, it can be noticed that on average, specimens with the less plastic soil will fail with a deformation 75% higher than that of specimens using highly plastic soil. Consequently, specimens with highly consistent infills will generally reach higher axial stress at failure but will take less time to be damaged as they present a more brittle behavior than specimens with softer infills do.

4.3.2 Stress-deformation-plasticity law equations

Based on previous results giving the relationship between the specimen axial stress and its deformation, on one hand, the soil plasticity and its shear strength on the other hand, it was possible to determine the correlation existing among those different parameters. In order to take into consideration, the infill properties other than its plasticity, namely its thickness and its cross-section, four different variation laws were defined, reflecting four configuration types (Fig.4, 5, 6, 7).

Case 1: Infills of small thickness and a small section

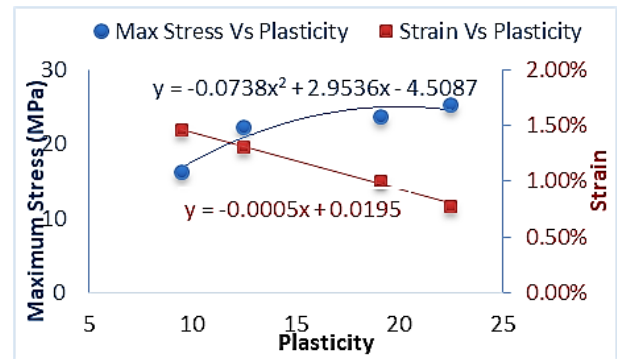


Fig.4: Trend curves for infills of small thickness and small section.

The variation law equations for thin infills with a small section are:

$$\sigma_{\max} = -0.0738P^2 + 2.9536P - 4.5087 \quad (\text{Maximum stress } \sigma_{\max} \text{ as a function of plasticity } P)$$

$$\epsilon_f = -0.0005P + 0.0195 \quad (\text{Strain at failure } \epsilon_f \text{ as a function of plasticity } P)$$

Case 2: Infills of small thickness and a large section

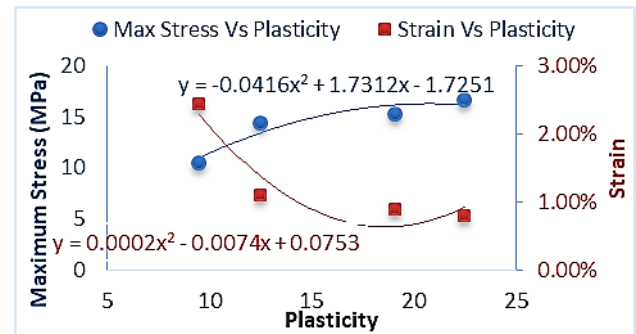


Fig.5: Trend curves for infills of small thickness and large section.

The variation law equations for thin infills with a large section are:

$$\sigma_{\max} = -0.0416P^2 + 1.7312P - 1.7251 \quad (\text{Maximum stress } \sigma_{\max} \text{ as a function of plasticity } P)$$

$$\epsilon_f = -0.0002P^2 - 0.0074P + 0.0753 \quad (\text{Strain at failure } \epsilon_f \text{ as a function of plasticity } P)$$

Case 3: Infills of large thickness and a small section

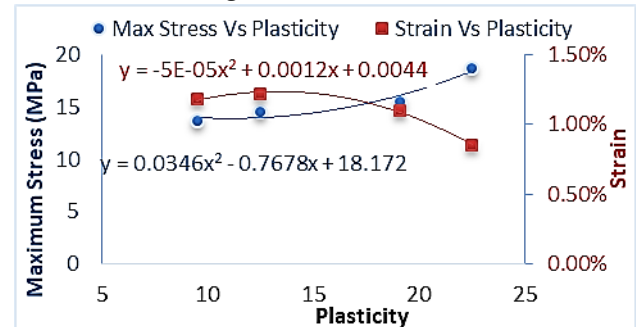


Fig.6: Trend curves for infills of large thickness and small section.

The variation law equations for this case are:
 $\sigma_{max} = -0.0346P^2 - 0.7678P - 18.172$ (Maximum stress σ_{max} as a function of plasticity P)
 $\epsilon_f = -0.00005P^2 + 0.0012P + 0.0044$ (Strain at failure ϵ_f as a function of plasticity P)

Case 4: Infills of large thickness and a large section

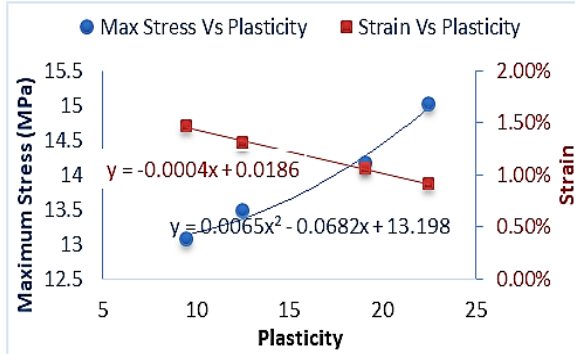


Fig.7: Trend curves for infills of large thickness and large section.

The variation law equations for this case are:
 $\sigma_{max} = 0.0065P^2 - 0.0682P - 13.198$ (Maximum stress σ_{max} as a function of plasticity P)
 $\epsilon_f = -0.0004P + 0.0186$ (Strain at failure ϵ_f as a function of plasticity P)

These variation law equations can serve to surmise the jointed rock mass behavior (maximum stress and strain at failure) when infills composing its structure can be evaluated with respect to their plasticity index and their size.

4.3.3 Influence of infill thickness and cross section

Two other parameters relevant to this study are the infill thickness and cross section. In this section, the extent to which a variation in the infill thickness would affect the overall behavior of the jointed cement block when the cross-section remains constant was investigated. The same analysis was then repeated for different cross sections with an unchanged infill thickness.

■ Influence of the infill thickness

The analysis of the infill thickness' influence has been based on results obtained from specimens with infills made of 100% clay and specimens with infills made of 40% clay+60% sand. Using these two types of soil materials helped to appreciate better, how the infill thickness effect on the specimen properties could possibly be enhanced or weakened by the soil plasticity.

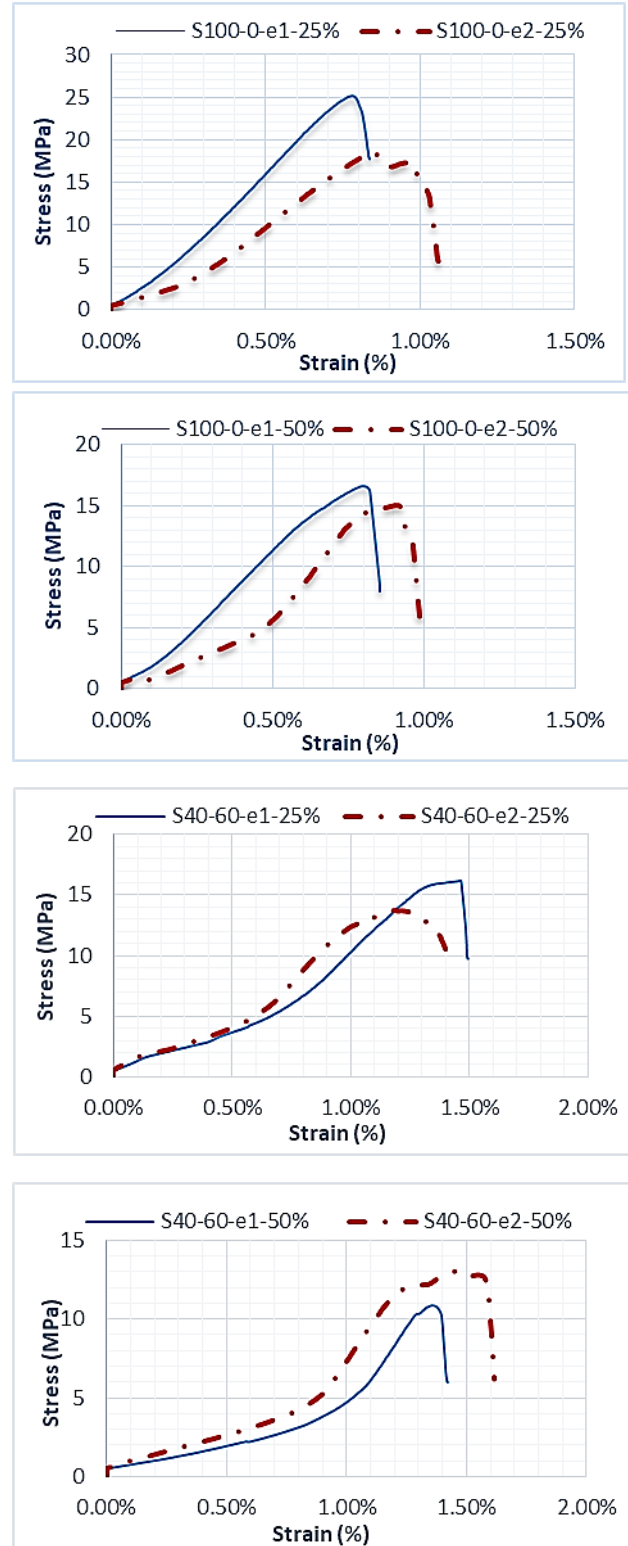


Fig.8: Curves of axial stress as a function of strain used to investigate the influence of the infill thickness on rock failure

Considering the diagrams above (Fig.8), the general observable trend is that a thicker infill will reduce the specimen compressive strength as well

as enable for a larger deformation at failure. For instance, in the case of specimen S100-0, it could be noticed that the maximum stress decreased by about 26% and the strain at failure increased by 24% for an infill' cross section of 25%.

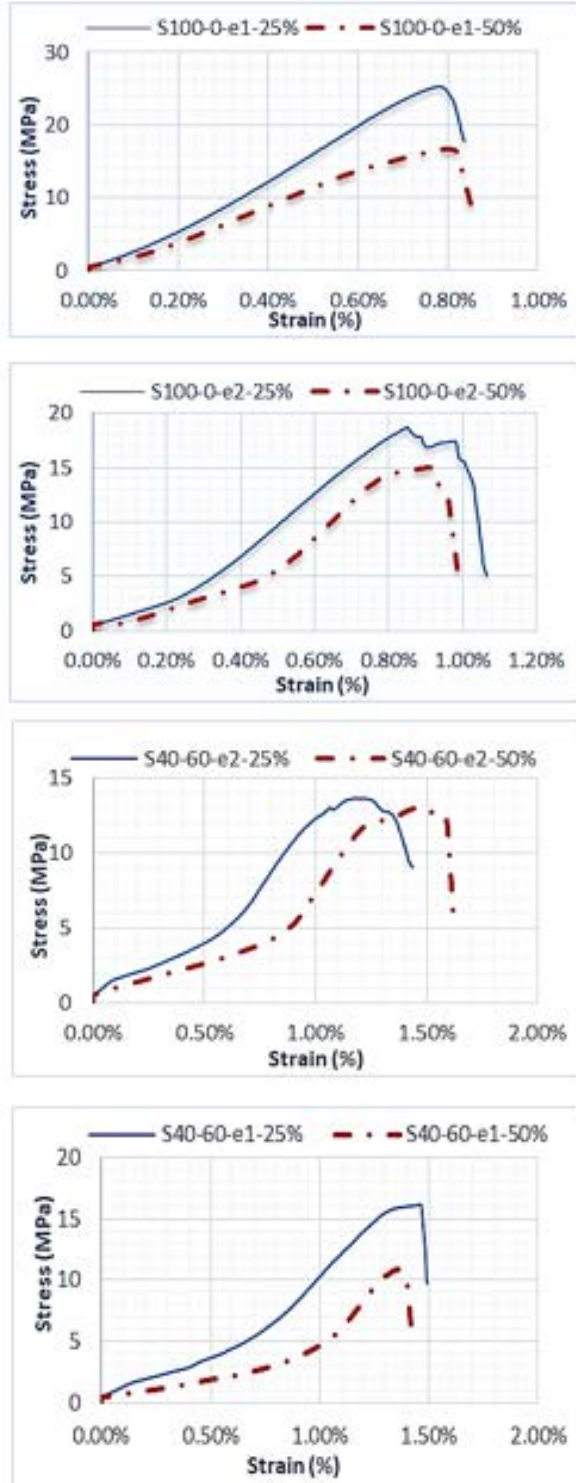


Fig.9: Curves of axial stress as a function of strain used to investigate the influence of the infill section on rock failure.

However, experimental results showed that this observation could be challenged if considering the specimen with the softest infill. This can be justified by the fact that there might be other elements such as the interaction between the rigid cement block surface and the softer soil material at their interface, which may have influenced the results.

▪ Influence of the infill cross section

Similarly, experimental results from specimens with 100% clay infill and those with 40%clay infills were used to analyze the influence of the infill cross section on the specimen behavior. The following diagrams were obtained (Fig.9).

When investigating the influence of the infill cross-section, it can be noticed that its impact will be more considerable on the specimen strength whereas the deformation would vary only slightly. In the specific case of specimen S100-0, the variation in the cross section induced a decrease by 34% of the specimen maximum stress while the deformation at failure changed by only 2%.

Generally, it could be expected that while a change in the infill thickness will have a clear consequence on both the rock strength and deformation, the infill cross-section variation will mainly impact the rock strength with limited influence on the rock deformation behavior.

4.3.4 Specimens failure mode

Uniaxial compression test was conducted on about 30 specimens, which displayed specific features regarding their failure mode. The singularities observed during the failure were related to cracks propagation within the cement block and the extent of compression of the infill at failure.

One major observation during specimen failure was that cracks propagation occurred essentially on the hard surface (made of cement) of the specimen.

During the compression test, the soil material used as an infill was highly compressed but in most cases did not fell off from the block, except for the soil type with the lowest consistency (40%clay, 60% sand) and lowest plasticity.

The general failure pattern consisted of some cracks created at the top edges of the specimen and then propagating following a diagonal line linking the crack starting point to both the right and left edges of the infill. When the crack reached the soil layer, the soil resistance came into play and in the case of soil with high consistency, its brittle behavior both favored an increase of the specimen total strength while allowing the crack to pass through and reach the bottom part of the cement

block, damaging it as well. However in the case of more sandy soil with therefore less consistency, once the cracks reached the soil layer, they easily powdered it, creating a sort of hole between the top and bottom cement blocks leading to a direct collapse of the entire specimen. The process of grinding and removing the soil layer in the specimen with infill of low consistency will favor its large deformation while severely reducing its block strength.

5. CONCLUSION

As one of the discontinuities with a high occurrence, joints have been subject to various research regarding their influence on the rock mass mechanical properties. In this study, the focus was put on how the plasticity index of the infill inside joints can affect both the joint behavior and the rock compressive strength. This work also investigated the relationship between infill thickness, cross-section, rock strength and deformation. It comes out that while the infill thickness remains the main parameter affecting to a large extent both the rock strength and its deformation, the infill cross section is nevertheless relevant essentially due to the fact that its increase might be damaging to the rock resistance as well. The obtained results also led to the observation that infill plasticity and consistency would not only impact the rock strength and deformation but would likewise affect the rock mode of failure. It was therefore observed that a stiff infill will favor a brittle behavior during the specimen failure while a soft infill will rather lead to a longer deformation phase with a decrease in the overall rock strength. In this study, based on the classification made on infill thickness and cross-section prior to the experimental test, it has been possible to define some law equations between the maximum stress and the infill plasticity on one hand, the deformation at failure and the infill plasticity on the other hand. Those equations could serve to provide a simple but practical insight on how plasticity would affect the rock mass behavior with regard to the infill thickness and cross section. However, to further understand the influence of infill plasticity on jointed rock mass behavior, future research should deeply investigate the behavior at the interface between the plastic material and the rock mass.

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