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Compressibility and Young's modulus of a filled joint under uniaxial compression

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Abstract: Weathering not only imposes a weakening effect but often widens critical and discrete geological discontinuities that induce further inhomogeneity into the weathered rock mass. Filled joint is one of the example of these geological discontinuities which has been frequently associated with numerous constructional problems. This paper discusses a laboratory investigation on the compressibility of a filled joint model under uniaxial loading. Laboratory test data was used to estimate the modulus of the infill and joint block. Using a *composite homogeneous model*, the modulus of the model filled joint was estimated. The resultant modulus is found to be lower than the modulus of joint block alone.

INTRODUCTION

Intense weathering of rock masses under a tropical climate is one of the major problems in civil engineering constructions. Weathering not only imposes a weakening effect on the rock mass but often widens critical and discrete geological discontinuities that induce further inhomogeneity into the weathered rock. The typical example of these discontinuities is filled joint. In Malaysia, the occurrence of filled joints in highly jointed crystalline rocks as granite is relatively common (Mohd Amin *et al.*, 2000). Figures 1 and 2 show this type of joint found at a granite outcrop (Papan Granite) in Lahat, Perak.

The occurrence of filled joints and various constructional problems caused by these discontinuities have been highlighted by many authors (Chernychev & Dearman, 1991; Moy & Hoek, 1989; Schubert & Schubert, 1993). Consequently, this has prompted many studies on the properties and behaviour of filled joint. In general, these studies show that the presence of infills in the joint apertures decreases the normal and shear stiffness of the host joint. The weakening effect is mainly due to the high compressibility and low shear strength exhibited by the infilling material.

The behaviour of filled joints is influenced by a number of interacting parameters as the roughness and nature of joint surfaces, and the thickness and type of infilling material (De Toledo & De Freitas, 1995; Mohd Amin & Kassim, 1999; Papaliangas *et al.*, 1993). In its simplest form, a filled joint is the result of the deposition of inwashed sediments in the joint aperture (Chernychev & Dearman, 1991; Mohd Amin *et al.*, 2000), the type of filled joint modelled in this study. Infills and joint blocks may also occur as layers of material of different weathering grades or banding patterns (Chernychev & Dearman, 1991; Ge, 1991; Mohd Amin *et al.*, 2000; Mohd Amin & Kassim, 1999). This type of filled joint is formed as a result of differential weathering along pre-existing joints. The inhomogeneous characteristic of filled joint makes it extremely difficult to account for in design. For example, materials of different weathering grade found in filled joint exhibit significant variations in engineering properties. Thus, the anticipated effect of this type of joint must be appropriately addressed and accounted for in designing suitable stabilisation methods. In addition, the presence of highly compressible material in the joint aperture may have negative impacts on certain types of rock reinforcement methods.

Aspects on joint compressibility have also been the interest of many researchers (Awang, 2000; Arora & Trivedi, 1992; Matthews & Clayton, 1992; B.S. 1377). In a highly jointed rock mass, a significant amount of deformation is contributed by the closure and slippage of joints. Intuitively, the the degree of deformability will depend upon several factors that include compressibility of the intact rock blocks, joint geometry, joint infill and joint wall compressive strength.

For rock masses with joints normal and parallel to the direction of loading, normal closure will dominate (Matthews & Clayton, 1992). For unfilled joint with interlocking asperities (i.e. matched joint), very small normal displacements are required for the interfacing joint walls to be in contact and the compressibility of the joint eventually approaches that of the intact rock. In this condition, the joint modulus is approximately equals to that of the intact joint blocks. For unmatched joint, the compressibility is increased by mismatches in the opposing joint wall geometries. Larger displacements are required before perfect contacts between the interfacing joint walls can be achieved. Under cyclic loading, this type of joint exhibits hysteretic behaviour (see Fig. 3) which is due to cumulative plastic yielding of the joint walls after each loading cycle (Bandis, 1993). Although the stiffness of the joint can be expected to increase after each loading cycle, it is most unlikely that the modulus will reach that of the intact joint block. A higher compressibility can be expected if the surface of both matched and unmatched joint walls have been subjected to a certain degree of

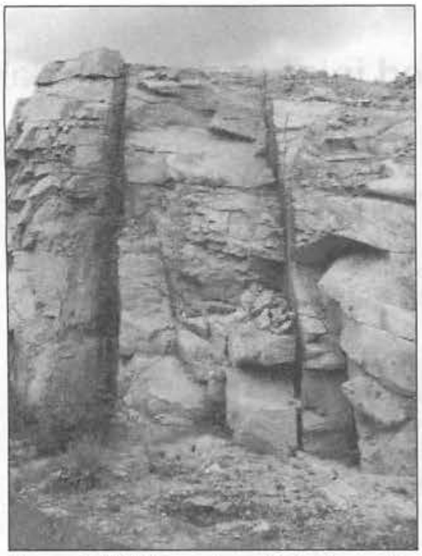

Figure 1. Highly weathered joint in granite outcrop.

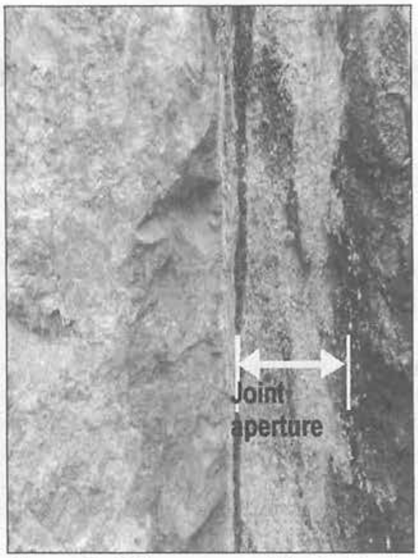

Figure 2. Joint aperture filled with in-washed sediments.

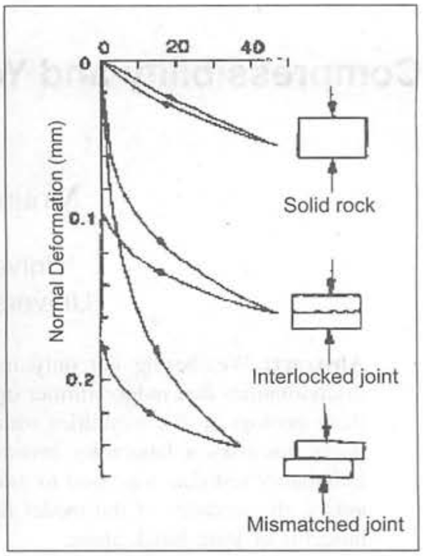

Figure 3. Normal compressibility of intact rock and joints (after Bandis, 1993).

weathering. When infill is present in the joint aperture, its compressibility is significantly affected by the properties of the infill. Unfortunately, infills are rarely stronger than the joint blocks. Thus, even a thin layer of infill may reduce the strength and stiffness of a joint as a result of less interaction between the stronger joint surfaces.

This paper highlights a laboratory investigation on the normal compressibility of a filled joint model. The study was conducted on a model consisting of artificial joint blocks of cast concrete with granite residual soil (RS) as infill. As part of an on-going research project, this initial study investigates the uniaxial deformational behaviour of the infill material and joint block, as separate entities. The respective uniaxial strains obtained were used to estimate the value Young's modulus for the joint block and the infill. Using a *composite homogeneous model*, the modulus obtained for both entities were then combined and consequently, the modulus of the filled joint was estimated. The resultant Young's modulus of the composite materials (joint blocks and infill) is found to be much lower than the joint blocks. The reduction is mainly due to the higher axial-strain exhibited by the weak infill presents in between the joint blocks.

LABORATORY TESTING

Two series of uniaxial compression tests were conducted; one series on the infill material and the other on the joint blocks.

The infill material used was a granite residual soil obtained from a nearby quarry in Kulai, Johor. Completely weathered (CW) granite was selected for the study as it is the weakest type of infill usually found in joint apertures. The sample originates from a coarse, porphyritic alkaline granite and sieve tests indicates that it is a well-graded sandy gravel with little fines. The original rock mass structure, material fabric and grain boundary strength are however, completely destroyed. The grains are not cemented and friable. Potash feldspars are mostly decomposed, being gritty and clayey, while most of the plagioclase grains are completely decomposed. Coarse mineral grains, especially feldspars and quartz, exhibit angular to sub-angular shapes with rough surfaces. Crushing of these angular-shaped and highly weathered mineral grains is thought to be the main contributor to the compressibility of the infill under high stresses (Mohd Amin *et al*., 2000; Mohd Amin & Kassim, 1999).

The joint blocks used were cylindrical shaped cast concrete blocks (153 mm diameter and 200 mm height). The mix design used is water:cement:sand:10 mm aggregate: 20 mm aggregate in proportions of 1:2.5:2.5:4:4. Cement additives (superplasticiser and silica fumes) were used to enhance the strength development. The idea of using actual rock material was abondoned at this preliminary stage mainly due to the difficulty of obtaining 153 mm diameter cylindrical rock samples, i.e. the diameter of CBR mould used for testing the infill. The reason for testing joint block of similar diameter as the infill sample was because in the next stage of this study, it is planned to conduct compression tests with the infill being sandwiched between the joint blocks. This would give a better picture on the compressive behaviour of filled joint.

Compression test on infill

Several factors were considered before compression test on the infill was carried out, these including the maximum grain size of the infill (more than 20 mm) and loading conditions. The latter in particular, should enable one to verify the deformational behaviour of the infill at low stresses and changing of material stiffness due to particle crushing. Therefore, a number of conditions were imposed on the test procedures:

Table 1. Summary of 'Oedometric compaction' test.

Test no.	Max. stress (kPa)	Initial thickness (mm)	Wt.of sample (gm)	Initial volume (cm^3)	Ini.dry density (Mg/m^3)	Initial voids ratio (e)	Initial porosity (n)	Relative density (%)
CBR1	1348.9	72.00	2038.67	1323.72	1.54	0.71	41.44	14.74
CBR2	1348.9	72.00	2039.23	1323.72	1.54	0.71	41.42	14.83
CBR3	1348.9	71.50	2039.50	1314.53	1.55	0.70	41.01	17.36
CBR4	815.7	72.00	2039.64	1323.72	1.54	0.71	41.41	14.90
CBR5	922.4	72.00	2039.51	1323.72	1.54	0.71	41.42	14.88
CBR6	709.1	72.00	2039.61	1323.72	1.54	0.71	41.41	14.90

- A 75mm thick sample was tested in a CBR mould (135mm dia & 127mm height). This is mainly to reduce variability in sample thickness and to compromise the ratio between maximum grain size and sample thickness and diameter.
- Using dry a *reconstituted* sample to reduce sample variability and for better control on the initial state of sample.
- Loading procedure is similar to the conventional consolidation test in clay (BS 1377, 1993) but with smaller load increment and shorter loading time.

Due to the loading configurations and the type of mould used, the test is termed as 'Oedometric-compaction test'. The size of the CBR mould used does not permit the test to be conducted on a conventional consolidation test equipment. Instead, tests were carried out on a shear box loading rig, taking advantage of its ability to maintain a constant normal load. The test set-up is as Figure 4.

About 2000 g of dry reconstituted sample of known gradings (Ong & Ong, 2000) was required to fill the mould to the required depth. Sample was spread evenly in the mould in 4 layers. A few tamping of the final layer is necessary to obtain the required thickness and a reasonably level surface. These procedures ensure all tested samples are of similar thickness and under loose condition (approximate minimum dry density 1.32 Mg/m^3).

An elaborate measurement of the uniaxial deformation of sample in the mould has been carried out (see Fig. 5). After sample surface has been levelled, the loading cap (weight 8.3 kg) is placed in the mould and turned one complete turn to obtain an even sample surface. Sample thickness after placing the loading cap is measured (depth 'D' in Fig. 5) and this is taken as the initial thickness (H_i) of sample and calculated as:

H_i = 127mm - ($\mathbf{D}_i$ + 25.8mm) = 101.2mm - $\mathbf{D}_i$. ......(1)

All dimensions and $\mathbf{D}_i$ in equation (1) are shown in Figure 5. The initial density and void ratio of the sample are calculated using the height H_i. The weight of the loading cap induces a small settlement in the sample and this results in a slightly higher initial density (about 15% higher than 1.32 Mg/m^3).

The load stirrup of the shear box (equivalent stress 16.0kPa) is then assembled and sample settlement is measured, giving sample height as:

H_1 = 101.2mm - $\mathbf{D}_1$ ....(2)

where, $\mathbf{D}_1$ is the measured depth and the difference (H_i - H_1) is the first settlement due to weight of load stirrup.

The LVDT is set in position and 'zeroed'. The loading beam of the shear box is then levelled. In this position the weight of the beam plus the stirrup is completely transferred onto the sample, giving an equivalent stress of 267 kPa. H_2 is calculated as:

H_2 = 101.2mm - $\mathbf{D}_2$ ....(3)

where, $\mathbf{D}_2$ is the measured depth after loading beam has been levelled. (H_i - H_2) is the total settlement due to 267 kPa stress. Measurements of $\mathbf{D}_i$, $\mathbf{D}_1$ and $\mathbf{D}_2$ are all taken at the same position and after allowing for a sufficient time (15-20 minutes) for sample to settle under the applied load.

Subsequent higher stresses are achieved by adding 3, 5, 10 up to 100 kg dead weight on the weight hanger. Each stress level is maintained for a period of time until there is no substantial settlement in the sample. The durations vary between 5 - 10 hours depending on the stress level. At this stage, all settlements are measured using a LVDT and continuously recorded using TML301 Tokyo Sikki data logger.

'Oedometric-compaction test' results

A total of 6 tests (CBR1 to CBR6) were carried out with maximum stress between 700 and 1350 kPa. The initial states of samples are summarised in Table 1. Hi, settlements at subsequent load and initial density are used to calculate the voids of sample after each loading stage. The plot of void ratio versus log of total vertical stress in Figure 6 shows the occurrence of the yield stress (point of inflection in the plot). This is the point of initiation of plastic/permanent deformation under oedometric (confined) compression. Observations made during the unloading stage showed that the sample behaves in a 'very stiff' and elastic manner, a behaviour normally associated with particle crushing. Visual inspection of samples after test confirms the occurrence of this phenomena. The yield stress at which crushing starts to occur was approximately 300 kPa.

Significant crushing of sample begins after the yield stress and this is shown by the increase in the reduction of void ratio in Figure 6. The yield point separates two phases of behaviour under oedometric compression. Before yield, compression mainly consists of volume reduction

Figure 4. Test set-up for CBR-consolidation test on large shear box apparatus.

induced by particles rearrangement. At stress levels beyond the yield point, the mechanism of deformation is mainly due to particle crushing.

Since there are two different modes of behaviour under compression, separated by the yield stress therefore, the following procedures in estimating the Young's modulus under compression are proposed. The plot of vertical strain vs. total vertical stress is shown in Figure 7a and 7b. As the value of stresses in the abscissa is normalised with the yield stress (300kPa) therefore, the value of the X-axis less than and greater than 1.0 represents the compressional behaviour before and after particle crushing, respectively. Stress-strain data at low stresses, Figure 7a, can be represented by secant Young's modulus defined at the onset of particle crushing. The concave shape in initial part of the curve was probably due to a sudden settlement during the placement of the load stirrup. The estimated secant or initial modulus, M_i, at this stress range is found to be 8.3 MPa. The stress-strain data beyond the yield point is presented in Figure 4(b). A linear behaviour still prevails in this stress region indicating a steady rate of reduction in void space due to crushing and continuous rearrangement of particles. Due to the reduction in voids and increase in particle contacts per unit volume, the modulus beyond yield point, M_y, is more than double the value of M_i and is estimated to be about 20.8 MPa. The value of M_i = 8.3 MPa is taken as the Young's modulus of the infill material under oedometric compression before crushing of mineral particles.

Unixial Compression Test on Joint Blocks

The compression test on model joint blocks is the normal UCT test described in ISRM (1981). However, the shape of sample tested (153mm diameter and 200 mm height; H/D ratio = 1.3) are different from the recommended dimensions. The reasons for choosing this specific shape has been explained earlier. Compressive load on the sample is applied using Matest C55 machine

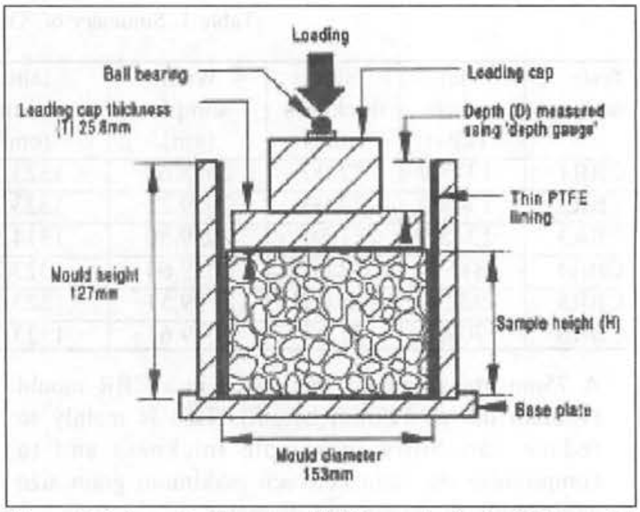

Figure 5. Schematic diagram of infill sample in the CBR mould.

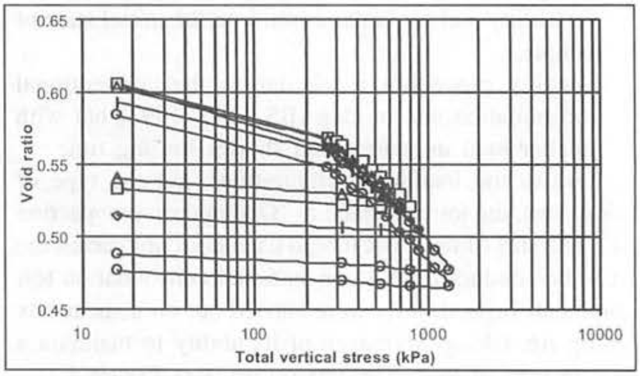

Figure 6. Void ratio vs total vertical stress.

(capacity 2000 kN) via steel spherical seats. Uniaxial strains of sample are measured using electric foil strain gauge, type TML PL 30 which is glued along the mid-section of its vertical axis. Strain readings are continuously recorded using a TML301 Tokyo Sikki data logger.

UCS test results

Three number joint blocks were tested after 28 days of curing (JB1, JB2 and JB3). The plot of uniaxial stress versus uniaxial strain for each sample is shown in Figure 8. The ultimate compressive strength varies between 50 and 56 MPa (with no correction for H/D ratio). The tangent modulus for each sample (at 50% ultimate compressive strength) is listed in Table 2. The average modulus calculated as 36 GPa, is taken as the Young's modulus of intact rock (joint block), E_{IR}.

MODULUS OF FILLED JOINT UNDER UNIAXIAL COMPRESSION

In the following paragraphs it will be shown that the presence of weak and highly weathered material in joint apertures will lead to a joint compression that is larger than an unfilled joint of similar dimensions. If the joint blocks and its infill behave elastically and isotropically

Table 2. Summary of UCS test results.

Sample no.	Ultimate UCS (MPa)	Strain at failure (%)	Avg. Young's mod. (GPa)
JB1	50.33	0.13	34
JB2	56.45	0.19	35
JB3	54.24	0.18	38

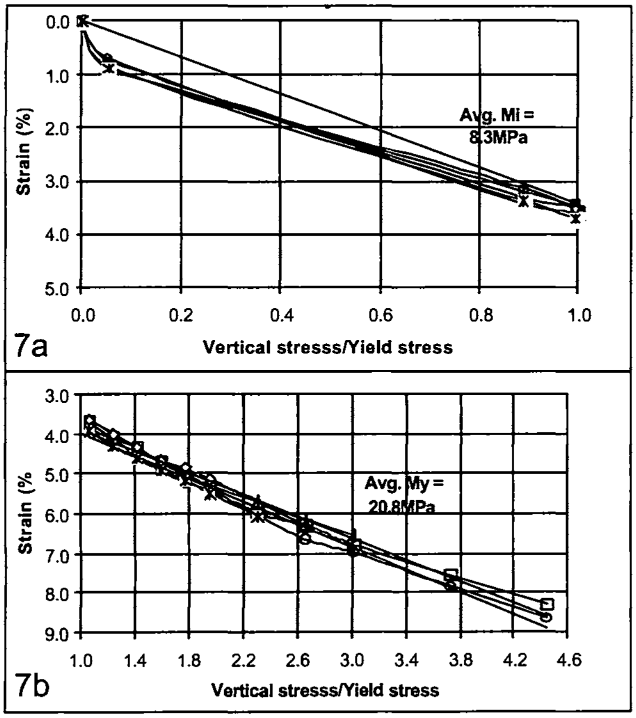

Figure 7. a) Strain vs (vertical stress/yield stress) before yield. b) Strain vs (vertical stress/yield stress) after yield.

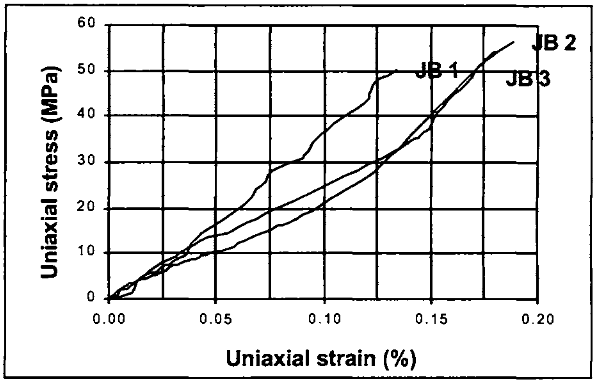

Figure 8. Uniaxial stress vs strain, joint block JB1, JB2 and JB3.

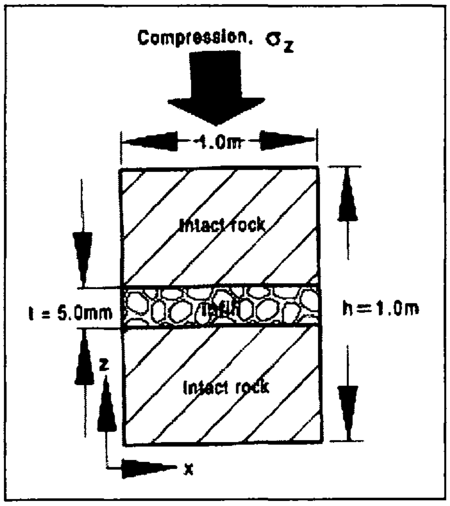

Figure 9. Composite homogeneous model of 1 m³ volume (after Wittke, 1990).

under compression, according to their elastic constants, the resultant modulus can be estimated from the volumetric contents of the intact rock (α) and the infill (β=1-a). Consider a composite homogeneous model of dimensions as depicted in Figure 6 (Wittke, 1990) and the following assumptions:

a) E_{IR} and (α) >> E_F and (β) where, E_{IR} and E_F are Young's modulus of intact rock and infill, respectively.
b) The lateral strain of the intact rock is very small and not affected by the infill.
c) No bulging of the infill at the joint edges thus, its lateral strain is approximately equal to that of the joint block.

Under compression σ_z, the uniaxial strains (ε_z) of the intact rock and infill are given as:

$$\varepsilon_{zIR} = \frac{\sigma_z}{E_{IR}} \text{ and } \varepsilon_{zF} = \frac{\sigma_z}{E_F} \quad \text{.................. (4)}$$

Assumption (a) portrays a state of confined lateral strain for the infill and therefore, its modulus is more appropriately represented by the oedometric modulus, E_{eod}. It can be shown that based on the volumetric content and the respective modulus (Fig. 9), the resultant uniaxial strain and modulus of the composite material (i.e. joint blocks and infill) can be presented as:

$$\bar{\varepsilon}_z = \alpha\frac{\sigma_z}{E_{IR}} + b\frac{\sigma_z}{E_{oedF}}, \text{ and } E_z = \frac{1}{\frac{\alpha}{E_{IR}} + \frac{\beta}{E_{oedF}}} \quad \text{...... (5)}$$

If fracturing of joint surfaces is ignored, the deformability of a filled joint is mainly contributed by its infilling. It has been discussed earlier that under one-dimensional compression, the deformation of coarse-grained material consists of compression due to particle rearrangement and crushing. At stress levels before particle crushing, the uniaxial stress-strain data represents the initial modulus, $\mathbf{M_i}$ of the material. The linear portion of the stress-strain data after crushing, gives the yield modulus, $\mathbf{M_y}$. The value of $\mathbf{M_i}$ and $\mathbf{M_y}$ were estimated from Figure 4. By subtituting a=0.995; b=0.005 (1 m³ volumetric content of composite materials shown in Fig. 9); E_{oedF}=M_i=8.3MPa and E_{IR}=36GPa into equation (5), the resultant modulus of the filled joint is 1.6 GPa (i.e. before crushing of the infill). It can be seen that the presence of 5mm infill in the joint aperture results in a significant reduction (about 20 times smaller) in the joint modulus. The reduction is mainly due to a higher axial-strain and lower modulus exhibited by the infill.

CONCLUSIONS

Using a composite homogeneous model, it has been shown that a significant reduction in joint stiffness may occur when weak material is present in its aperture. The reduction is due to the higher axial-strain and lower Young's modulus exhibited by the infill. For typical infill like CW granite, crushing of its highly weathered mineral grains contributes significantly to joint compressibility.

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