The increase in Young's modulus under uniaxial compression test

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Abstract

The sources of nonlinear deformation in hard rock under short term uniaxial compression can be attributed to crack closure, sliding, compaction and crack generation. The common approach to finding the Young's modulus of a "hard rock" is to determine the linear part of stress-strain curve. However, it is usually a difficult task, although several methods of resolving it have been proposed in the past. We believe that in some rock types there is no linear part as such and provide evidence to support the fact that nonlinear deformation contributed by crack closure, sliding and compaction in different degrees could co-exist within the same stress range. We demonstrate that the change in tangent modulus under different stress levels is attributable to the combination of crack closure, sliding and dilatancy. The difference in tangent modulus under different stress levels could reach more than 20GPa in some rocks. We have also found that the nonlinear deformation contributed by irreversible sliding, compaction and even dilatancy increases the rock stiffness in the second loading. This phenomenon was found under loads ranging from 15% to 95% of UCS.

Keywords: Crack closure; Sliding; Dilatancy; Modulus; Residual strain; Rock stiffness.

1 Introduction

The deformation of a rock samples can be classified to linear elastic and inelastic deformation. The sources of inelastic deformation are: (1) closure of pre-existing cracks, (2) sliding of pre-existing cracks, (3) dilatancy caused by wing crack initiation and propagation, and (4) compaction caused by pore/void collapse. The influence of creeping and rheology properties is assumed to be very small or undetectable in the short term (<1 hr) loading cycle in the laboratory and will not be discussed in this paper.

The closure of pre-existing cracks under stress and compaction caused by

pore/void collapse would increase the stiffness of rock, because the size of area that is subjected to load increases. The sliding of pre-existing cracks and crack growth would reduce the tangent modulus, because of the additional strain contributed by sliding or crack growth. Depending on the amount of strain introduced by each mechanism at a specific stress level, the combination of these four mechanisms increases or decreases the value of tangent modulus during loading.

In the literature, the four mechanisms are often described separately as the occurrence of each of them is attributed to different stress levels, and it is assumed that ranges of stress levels associated with each mechanism do not intersect [1-12]. In [13] it was considered a combined effect of crack closure and crack sliding occurred and the authors developed a model with a good predictive power. It is believed the sequence of these mechanisms begins with the crack closure when the rock sample was loaded. It only occurs at the low stress and introduces an increase in tangent modulus, resulting in a nonlinear region at the beginning of the stress strain-curve. It was suggested in [2] that in hard rock, the stress region of crack closure might be very small or not existent. It was assumed that the linear elastic deformation that takes place after the crack closure process finishes, followed then by the stage of stable crack initiation generating inelastic strain [1-12]. The wing cracks produced by sliding over pre-existing cracks produce mainly lateral inelastic deformation.

Following the assumption that the phenomena of crack closure, elastic deformation and crack growth are attributable to different stress levels, a considerable body of research has been directed towards identifying the linear part of the stress-strain curve in order to determine the Young's modulus and Poisson's ratio [4, 6-8, 10-12, 14-16] and to calculate the values of dilatancy [3, 4, 7, 8, 10, 11]. Since the elastic deformation modulus represents the solid (uncracked) rock without the influence of crack closure, sliding, and/or crack propagation, the difference between measured strain and the elastic strain calculated from the modulus will be the inelastic strain produced by the crack closure at the low stress or by the dilatancy at the high stress. From here one can delineate separate mechanisms of non-elastic deformation and identify the stages of crack closure and growth (e.g., [17-19]).

However, in many cases the elastic part of deformation might be too small to

identify reliably. For instance, to the best of our knowledge, there is no evidence in the literature to support that crack closure will only exist in the low stress level before crack sliding. Hence the elastic part might not exist due to the co-existence of crack closure, crack sliding and crack propagation mechanisms at the mid stress levels.

The phenomenon of overlapping between crack closure, sliding and propagation can be found at all stress level by utilising the tangent modulus variations obtained from the unloading cycle. Because the Young's modulus in a rock without cracks is higher than in a rock with cracks, the tangent modulus measured at the initial unloading process can represent an uncracked solid. Indeed, the crack which has slid in the process of loading would not immediately slide in the opposite direction when the load is reduced due to friction [2, 20]. Therefore, under low stress levels when no crack growth is yet possible, the difference in the tangent modulus between end of loading and initial unloading process is due to sliding over pre-existing cracks.

The stress-strain curves [21] show that the tangent modulus of initial unloading process is always higher than the tangent modulus at same stress in the loading process (Figure 1). Accordingly, the sliding over the pre-existing crack exists in the low stress area (30% of the maximum strain). The stress-strain curve also showed that the region of sliding co-exists with the region of crack closure, because the tangent modulus increase was also observed at this stress level. Therefore, the crack closure and sliding occurred together in this case.

This evaluation of the existence of the linear part in the axial stress-strain curve can be extended further to the volumetric strain. It was believed that the lateral strain is elastic at the low stress, followed by an inelastic increase caused by opening of the wings initiated by sliding over pre-existing cracks [2, 3]. A typical volumetric strain curve appears to show 3 major regions: (1) crack closure region; (2) elastic deformation; and (3) crack growth, Figure 2.

Based on the previous discussion, the sliding and/or crack closure can occur at any level of stress. The lateral stress-strain curve will not be linear before the onset of dilatancy due to the inelastic strain introduced by sliding and crack closure. It is not linear after the onset of the dilatancy, either. Since both axial and lateral strain could

be affected by crack closure and sliding at all stress level, the volumetric strain could be nonlinear at all stress level. It would be very difficult to distinguish the elastic part from the inelastic parts of the deformation by stress-strain curve or volumetric strain curve in the loading process.

To summarise, the non-linear deformation mechanisms associated with the crack closure, crack sliding and crack propagation can occur simultaneously resulting in changes in the overall stiffness of the rock. To evaluate the method of extracting the inelastic strain from the total strain by finding the elastic part, we analysed the dependence of the tangent moduli vs. stress in different rock types in order to establish the trend of tangent moduli in different rock types. Then, we investigated the change in Young's modulus under repeated load. The inelastic strain contributed by the closure of pre-existing cracks and reversible sliding diminishes to zero when the applied stress is absent and it reoccurs under repeated load. Hence, the amount of closure of pre-existing cracks and reversible sliding remains the same at the same stress level, regardless of the number of loading cycles. Since the amount of the irreversible sliding, crack growth, and compaction can be different at the same stress level in each loading cycle, the trend of the tangent modulus at the first load and the increase of secant modulus in the second load allow us to estimate the source of inelastic and irreversible strain. There are 198 samples from 13 different locations were tested and analysed in this paper.

2 Experimental apparatus and rock properties

We tested cylindrical samples of porphyry, slate, sandstone, felsic volcanics, metasediment, ultramafic, pegmatitic granite and volcanic sediment from 13 locations (12 boreholes, 198 samples) under uniaxial compression. The samples were 18-19mm in diameter and 40mm- 45mm in length, as shown in Table 1. All samples were prepared in accordance with ISRM standard for unconfined compressive strength [22]. The samples were loaded using a servo-controlled loading machine of 5t capacity. The load was displacement-controlled, applied by the movement of the upper platform, while the bottom platform was fixed.

We used glued cross type strain gauges (Figure 3a), which ensure simultaneous measurements of the axial and lateral strains. All samples were subjected to 2 loading cycles under a constant loading/unloading rate of 7~9MPa/min (Figure 3b). The

average strain was calculated by taking average of readings of 4 strain gauges. The tangent moduli of 1st loading cycle were calculated by the moving average method applying to the average stress-strain curve.

3 Test results and discussion

3.1 The trend of tangent modulus at 1st cycle

The stress dependence of the tangent modulus can be classified into 3 types: increase, constant, and decrease. The tangent modulus of the increase type usually reduces its value at the beginning of loading (the stress of less than 15MPa in our tests). Then the value of modulus increases steadily until high stress level before it drops and the sample fails. The increase of modulus could be from 5 to 30MPa and appears to be rock type dependent. This response (i.e. modulus of increase type) is the most common type in our experience. The mechanism of modulus increase is believed to be crack closure. Figure 4 shows an increase of 26GPa during loading in an ultramafic rock sample.

The tangent modulus of the constant type is usually unchanged in the region from mid to high stress, followed by a dramatic drop in the modulus right before failing. The value of modulus of this type does not represent pure elastic deformation. Figure 5 shows a porphyry sample with very little increase (<2GPa) in tangent modulus. The close-to-constant value of modulus could be a misleading phenomenon, as it seemed to indicate that there was no crack closure or crack propagation. However, the slope of volumetric strain shows a slight increase in the value when the stress is increased. Therefore, the volume change and the crack closure/propagation was taking place in this case.

The tangent modulus of the reduce type lowers its value from the beginning of loading until the sample fails, Figure 6. A possible mechanism of this type of behaviour is sliding over pre-existing cracks; as the stress increases the number of cracks where sliding is possible increases as well, effecting the modulus reduction. Since the modulus decreases consistently from the very low stress when no crack growth is yet possible, the dilatancy-producing crack growth is expected not to be the dominant mechanism. This conclusion is confirmed by the fact that the volumetric strain vs. stress is a straight line (the slope of volumetric strain is unchanged by the

increase in stress). The modulus might reduce more steeply when the stress is close to the failure stress (i.e. the UCS). At this stress level the crack growth is expected to occur and contribute to the modulus decrease.

3.2 The overlapping between the regions of crack closure, sliding and crack growth

It is a common approach to find the linear part of the volumetric strain by drawing a straight line to match part of the curve, for example the dash line in Figure 4b. However, it is not as accurate as it looks. The slope of the volumetric strain does not show any linear part in the curve. Hence it is not possible to find the elastic deformation region by volumetric strain. Furthermore, according to the Figure 4a, there is no linear part apparent in the stress-strain curve, because the tangent modulus constantly changes during the whole loading cycle. Since the linear elastic deformation in the axial stress-strain curve does not exist independently, but rather in a combination with non-elastic one, it is possible that the crack closure process is still in place when the sliding and/or dilatancy have already started.

Figures 5 and 6 show a similar situation. The tangent modulus in Figure 5 remains effectively constant during whole loading cycle. However, the value of modulus does not represent linear elastic behaviour due to the fact that there is observed a non-elastic change in the volume. Figure 6 shows no change in the volume, but the crack sliding had to place because of the consistent modulus reduction. Therefore, in these 2 cases, the modulus of rock unaffected by crack closure, sliding, and growth cannot be determined.

We have not found any sample with constant modulus but without inelastic volumetric strain. Subsequently, in all 198 samples the pure elastic modulus of rock was not measurable.

3.3 The increase of the modulus from 1st cycle to 2nd cycle

According to our results from the 198 samples, the residual strain in a completed load-unload cycle of the 1st cycle is always observed. The amount of residual strain can vary from less than 1% to more than 50% of the total reversible strain. The sources of residual strain in our tests could be:

1. The irreversible sliding in the loading cycle: The friction between the crack surfaces stops the crack sliding back when the load is removed. The volumetric strain is unchanged, because there is no increase in volume. The crack might/ might not slide back when a second cycle of load-unload is again applied with the peak stress higher than the previous peak stress. The stiffness of the rock increases when the applied load is in the same direction again due to the irreversible sliding. An example of this case is shown in Figure 6a.
2. The breakage of asperities on the crack surfaces when the crack slides: The surfaces of an open crack might not be smooth and the sharp points might break when crack slides (Figure 7). The volumetric strain reduces because the breakage occurs together with crack closure. Some energy is consumed (dissipated) during the breakage and the crack would not fully slide back to the original position during the unloading cycle. Therefore, the volume of the crack reduces and the stiffness of the rock increases when a second cycle is applied load axially. It might seem to be controversial that the stiffness of the rock still increases after the load introduces some damage (i.e. breakage of the asperities) to the rock. However, the area which was subjected to the load increases after the asperities are broken and the crack size reduced. The sample is more “compacted” after the breakage. The possible example of this case is shown in Figure 4a.
3. Pore collapse: This is similar to case 2 but there is no movement in the lateral direction in this case. The sample has to be porous and it requires high energy to collapse the pores. In our samples, which are mostly hard rocks with modulus in the range of 40-100GPa, it might be less likely to occur than for cases 1 and 2.

We believe cases 1 and 2 are the more likely to be the source of residual strain and both of them are relevant to the sliding mechanism, which can occur at any level of stress. In addition to the residual strain of case 2, the acoustic emission can also be generated by the breakage of asperities on the crack surface during loading. If the stress path/distribution at the 2nd load is the same/very similar with that of the 1st load, the asperities would not break until the stress level at the 2nd load reaches the previous maximum stress. Hence, the well-known Kaiser effect is observed. However, in this case, the Kaiser effect will only be present when the previous maximum load is

subjected in the laboratory. The 1st load is needed to “crush and erase” all the asperities on the crack surface, so the acoustic activities at the 2nd load can show the Kaiser effect. If the rock was extracted from underground, the confinement has been removed during the extraction and the crack was opened (Figure 7). In this case, all the asperities on the crack surface are generated by removing the confinement. Hence, it is expected the acoustic activities at the 1st load would be very high until the stress level reaches the in situ stress. This phenomenon of acoustic emission would be the opposite of the Kaiser effect, because all the cracks are closed and there is lack of asperity to break after the stress reaches the in situ stress. This “opposite Kaiser effect” was observed in some of our tests especially in soft to median strength rock.

Furthermore, the higher the applied stress, the higher the initial unloading modulus, Figure 1, would be. It suggests that different levels of stress could mobilize different cracks or different amount of cracks to slide. The initial unloading modulus does not represent the “solid rock” but represents the rock mass with specific part of the cracks “locked” due to the applied peak stress. Therefore, in the same type of rock, the amount of the cracks that were locked during loading should have a particular relationship with the amount of residual strain. The amount of residual strain at the 1st cycle should also have a particular relationship with the increase in secant modulus at the 2nd cycle. According to Figure 8, the difference between secant moduli at the 1st and 2nd cycles depends on the amount of $\Delta\varepsilon$ and ε_r :

$$\frac{E_2}{E_1} = \frac{\varepsilon_m}{\varepsilon_m + \Delta\varepsilon - \varepsilon_r} = 1 + \frac{\varepsilon_r - \Delta\varepsilon}{\varepsilon_m + \Delta\varepsilon - \varepsilon_r} \quad (1)$$

where E_1 is the secant modulus at 1st cycle, E_2 is the secant modulus at 2nd cycle. ε_m , ε_r , and $\Delta\varepsilon$ are same as Figure 8.

In all 198 tests, $\Delta\varepsilon$ is much smaller than ε_r and it is less than 4% of ε_m . We assume $\Delta\varepsilon \ll \varepsilon_m$ develop (1) in Taylor series with respect to small parameter $\Delta\varepsilon/\varepsilon_m$ keeping only the linear term. Assuming that $\Delta\varepsilon = r\varepsilon_r$, where r can be different in different rock types we obtain:

$$\frac{E_2}{E_1} = 1 + (1 - r) \frac{\varepsilon_r}{\varepsilon_m - \varepsilon_r} \quad (2)$$

Formula (2) predicts a linear relationship between the increase in the secant modulus E_2/E_1 and the portion of residual strain ($\frac{\varepsilon_r}{\varepsilon_m - \varepsilon_r}$) in each rock type. Figure 9 shows the results of this relationship obtained in our tests and the fitted regressions lines. Similar observation can be made by looking at the experimental data found in the literature [23]. We have calculated the portion of residual strain and the secant modulus visually from the figures in [23]. The results of the determination of r are shown in Figure 10.

The value of r in some locations might not be as accurate as other locations because the residual strain is very small and the electronic noise can cause more significant errors. The size of inclusion in the samples could also introduce scattering to the value of r . It is suggested that the diameter of the sample should be related to the size of the largest grain in the rock by the ratio of at least 10:1 [22], but the granular inclusions in some samples are larger than 2mm. This issue was overcome by conducting the repetition tests. The number of samples tested in one location (borehole) is more than 10 and the sub-coring was done in 6 different orientations at each borehole. The results of samples from different lithologies, different foliation/bedding angles and different orientations are similar and the R^2 in Figure 11 is 0.98. Hence, the effect of scattering due to grain size is minor. The value of r is between 0.1 to 0.2 in 11 out of 13 locations. Figure 11 shows that the average value of r for all 198 samples is 0.12.

In [24], the mineral content in the rock mass controls the dynamic and static moduli. The ratio of dynamic to static moduli is also closely linked to the crack density/intensity and level of foliation, which are potential factors of the value of r . In our results, the ratio of dynamic to static moduli varies from sample to sample but the relationship between residual strain and the increase in secant modulus is unchanged. Hence, we believe that other than crack density/intensity, there is another parameter which dominates the increase in secant modulus.

4 Conclusion

There are several approaches to separate the inelastic deformation from total strain. It has always been a difficult task to find the linear elastic part of the stress-strain curve that represents the behaviour of the solid rock without pre-existing cracks. In order to evaluate the common approach used on finding the elastic property of a solid rock, we have tested 198 samples from 12 locations and completed 2 loading/unloading uniaxial compressive cycles. We found that the trend of tangent modulus at the 1st cycle can be expressed by 3 types of behaviour: increase type, constant type, and reduce type. All 3 types of behaviour cannot truly represent the modulus of solid material, and we contend there is an overlapping of crack closure, sliding and crack propagation in the stress-strain curve. Therefore, the “finding elastic part” from stress-strain curve might mislead the understanding of real rock behaviour.

The irreversible sliding caused by the friction between the crack surfaces stops the crack sliding back when the load is removed. The stiffness of the rock increases when the applied load is in the same direction again due to the friction. The breakage of asperities on the crack surfaces occurs together with crack closure or sliding. The energy dissipates during the breakage so the crack would not fully re-open or slide back to the original position when the load is removed. Hence, the sample is more “compacted” after the breakage and the reduction of crack volume due to breakage of asperity enables the stiffness of the rock increase under repeated load.

Contrary to a common belief that the rock reduces its stiffness after repeated loads, the experimental result shows it may actually increase. The reduction in stiffness caused by the increase of crack concentration after the initiation of dilatancy is much smaller than the increment that irreversible sliding and the breakage of asperity on the crack surface creates. Furthermore, this increase is controlled by the residual strain of the first unloading. We experimentally showed that the secant modulus of the 2nd cycle is higher than it at the 1st cycle, and the increase is proportional to a certain portion of residual strain. This relationship is independent of the maximum stress level a rock had been subjected to and it seems to be similar for different rock types.

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Table 1. Details of the tested rock samples. The samples are orientated in various directions and the overburden stress does not represent the in situ stress level of each sample.

Location and sample ID		Max. applied stress (MPa)	Secant modulus at 1 st cycle (GPa)	Secant modulus at 2 nd cycle (GPa)	Poisson's ratio	Dynamic modulus (GPa)	Comment
FE4	A3	60	46.5	50.9	0.23	59.4	Quartz diorite porphyry complex from 898m in depth (overburden stress 25.7MPa). No visible foliation. The crystal size is coarse sand or very coarse sand.
	A4	67	41.6	46.0	0.20	67.6	
	B1	75	47.0	49.9	0.24	62.5	
	B4	72	48.4	52.8	0.24	64.1	
	C2	61	28.8	32.7	0.28	50.2	
	C3	65	49.4	54.0	0.23	60.3	
	D1	65	35.2	38.8	0.21	55.3	
	D2	60	24.0	27.5	0.31	38.1	
	D4	67	40.9	45.9	0.22	59.7	
	E2	44	32.1	36.9	0.17	58.8	
	E3	56	48.1	52.3	0.24	63.8	
	E4	58	51.5	55.3	0.26	62.7	
	F2	62	27.8	32.9	0.27	51.3	
	F4	50	51.1	56.0	0.20	63.8	
FE5	A2	70	46.5	50.9	0.20	69.9	Quartz diorite porphyry complex from 887m in depth (overburden stress 25.2MPa). No visible foliation. The crystal size is coarse sand with few granule inclusions occasionally.
	A3	68	41.6	46.0	0.19	64.2	
	A4	75	47.0	49.9	0.28	49.5	
	B2	75	48.4	52.8	0.25	65.9	
	B3	35	28.8	32.7	0.15	51.8	
	B4	75	49.8	54.0	0.26	64.3	
	C2	75	41.4	45.8	0.28	63.3	
	C3	60	32.6	37.2	0.26	60.1	
	C4	75	54.8	58.3	0.28	65.5	
	D2	65	30.5	34.4	0.29	62.5	
	D3	75	54.7	57.7	0.27	63.4	
	D4	75	58.9	61.4	0.22	68.6	
	E2	51	51.0	54.7	0.26	64.5	
	E3	75	53.1	56.0	0.20	69.6	
	E4	75	57.2	59.4	0.29	63.6	
	F2	75	49.2	52.8	0.27	64.6	
	F3	65	61.8	64.7	0.16	59.0	

	F4	75	54.2	58.1	0.27	69.0	
WA 45	A1	65	44.8	51.7	0.16	64.2	Metasediment from 1190m in depth (overburden stress 33.7MPa). Strong foliation. The range of crystal size is from coarse sand to granule.
	A2	70	46.2	53.2	0.17	63.5	
	A3	65	58.3	64.6	0.11	77.5	
	B1	70	45.7	50.9	0.12	39.7	
	B3	65	34.7	41.0	0.10	28.8	
	C1	70	38.0	41.9	0.08	50.2	
	C2	65	44.4	48.3	0.08	76.4	
	C3	65	31.4	36.3	0.11	41.6	
	D1	60	40.3	45.8	0.12	52.4	
	D2	69	28.4	37.5	0.06	29.4	
	D3	55	19.6	27.9	0.11	27.5	
	E2	63	33.5	38.2	0.11	47.1	
	E3	56	37.2	43.0	0.10	69.4	
	F1	70	50.7	59.8	0.17	66.0	
	F2	55	24.5	29.0	0.09	37.0	
WA 51	A2	63	98.8	112.0	0.32	118.3	Ultramafic rock from 1206m in depth (overburden stress 39.8MPa). No visible foliation. The range of crystal size is from very coarse sand to granule.
	A3	65	87.8	97.1	0.22	119.2	
	A4	49	89.4	102.3	0.14		
	B1	60	109.0	116.3	0.16	141.4	
	B2	65	110.4	116.7	0.21	131.3	
	B3	60	115.0	125.5	0.18	129.1	
	C1	73	89.3	94.4	0.14	117.9	
	C2	80	137.1	146.0	0.19	149.3	
	C3	65	106.7	113.0	0.15	144.8	
	D1	61	111.1	120.4	0.18	136.1	
	D2	70	108.7	117.0	0.21	128.3	
	E1	73	112.0	116.8	0.19	147.7	
	E2	65	109.6	115.2	0.15	130.3	
	E3	65	130.6	136.6	0.22	142.2	
	F3	70	107.4	115.4	0.15	156.4	
H 782	A1	83	59.3	60.7	0.16	61.1	Porphyry from 1549m in depth (overburden stress 39.6MPa). No visible foliation. The range of crystal size is from
	A2	90	60.0	60.8	0.18	67.3	
	A3	102	58.9	60.2	0.17	56.0	
	B1	90	65.6	66.9	0.17	63.7	
	B3	81	51.7	53.4	0.19	56.8	
	B4	100	53.8	55.3	0.14	56.7	

	C1	90	63.4	64.6	0.17	65.2	medium sand to granule.
	C2	83	67.2	68.2	0.15	70.0	
	C4	90	58.8	60.2	0.23	62.1	
	D1	95	59.7	60.5	0.20	68.1	
	D2	90	56.1	57.3	0.20	64.4	
	D4	90	60.0	61.4	0.16	62.8	
	E1	85	61.4	62.3	0.20	65.3	
	E2	83	53.2	54.4	0.19	60.9	
	E3	90	58.6	59.7	0.23	61.2	
	F1	90	64.6	65.3	0.22	67.8	
	F3	90	61.3	62.7	0.21	64.3	
H 784s	A2	80	38.3	40.0	0.13	47.4	Porphyry from 1614m in depth (overburden stress 40.2MPa).
	A4	95	41.9	43.4	0.16	46.2	
	A5	75	74.4	75.6	0.12	54.7	
	B1	95	40.6	42.0	0.21	46.3	No visible foliation. The crystal size is generally less than 2mm with few granule inclusions occasionally.
	B2	74	72.6	74.6	0.14	72.6	
	B4	66	37.6	39.1	0.13	45.0	
	C2	80	36.8	38.9	0.18	42.8	
	C3	70	48.8	50.0	0.19	48.0	
	C4	90	39.3	41.3	0.19	45.0	
	D2	85	36.4	39.4	0.19	41.7	
	D3	86	44.4	45.7	0.19	46.9	
	E1	90	45.7	46.9	0.19	45.3	
	E2	65	37.0	38.7	0.14	38.0	
	E3	70	26.8	28.7	0.17	33.8	
	F1	95	41.4	41.0	0.18	50.2	
	F2	85	39.8	41.3	0.23	45.8	
	F3	75	38.0	39.7	0.18	34.7	
H 784d	A2	85	61.2	62.0	0.20	55.5	Porphyry from 1637m in depth (overburden stress 42.5MPa).
	A3	82	65.7	66.6	0.22	64.2	
	A5	85	60.5	61.4	0.19	54.4	
	B2	80	56.0	57.4	0.19	60.0	No visible foliation. The crystal size is generally less than 2mm with few granule inclusions occasionally.
	B3	80	62.2	63.3	0.21	68.8	
	B4	80	60.6	61.7	0.20	61.3	
	C1	85	65.9	66.9	0.19	67.6	
	C3	55	62.8	63.9	0.18	70.1	
	C4	85	64.9	66.0	0.21	62.5	

	D1	80	61.1	62.2	0.21	64.4	
	D2	78	67.8	68.8	0.19	65.5	
	D3	77	71.2	72.2	0.16	72.0	
	E1	80	61.4	62.9	0.13	70.1	
	E3	80	61.6	62.8	0.20	69.0	
	E4	65	64.5	65.7	0.19	64.2	
	F1	70	53.8	55.2	0.17	60.9	
	F3	80	64.3	65.4	0.22	62.4	
	F4	90	59.2	60.2	0.20	67.3	
FL	A1	45	35.3	42.5	0.20	66.0	Pegmatitic granite from 320m in depth (overburden stress 8.5MPa).
	A3	45	50.9	54.5	0.37	46.0	
	B1	46	73.6	77.0	0.19	90.0	
	B2	45	62.8	64.4	0.23	77.3	No visible foliation. The crystal size is generally between 1-4mm, with occasionally large inclusions (>5mm).
	B3	45	45.8	46.4	0.18	66.5	
	C2	45	57.2	61.5	0.16	83.4	
	C3	45	59.0	62.4	0.20	68.1	
	D1	45	58.8	61.5	0.35	49.2	
	D2	45	39.9	43.9	0.40	34.2	
	D3	45	53.4	57.1	0.45	23.6	
	E1	46	74.1	76.8	0.39	57.3	
	E2	45	43.6	47.3	0.30	61.0	
	E3	45	37.6	39.5	0.34	49.4	
	F1	45	61.5	65.1	0.37	50.6	
	F2	45	42.7	45.0	0.38	44.7	
	F3	45	49.7	53.2	0.38	45.7	
CSA	A1	100	63.0	64.5	0.26	53.8	Sandstone from 1531m in depth (overburden stress 43MPa).
	A3	95	59.6	61.9	0.28	54.2	
	A4	70	70.6	72.6	0.22	66.7	
	B1	110	73.2	75.5	0.30	80.1	No visible foliation. The range of grain size is from coarse silt to very fine sand.
	B2	94	90.6	91.9	0.23	90.9	
	B3	90	88.7	89.8	0.22	92.6	
	C1	90	81.0	81.9	0.23	86.4	
	C3	95	79.3	79.8	0.24	82.4	
	C4	90	80.1	81.1	0.25	84.5	
	D2	76	79.8	82.1	0.26	84.8	
	D3	70	83.0	84.1	0.24	85.3	
	E1	75	90.8	90.8	0.20	95.1	

	E2	90	88.7	90.1	0.22	86.9	
	E3	90	87.4	88.5	0.20	91.9	
	F1	110	76.7	78.4	0.23	76.2	
	F3	95	72.7	74.2	0.25	73.9	
PR2	D1	23	41.4	42.5	0.31	52.5	Slate from 170m in depth (overburden stress 4.8MPa). Strong foliation, grain size is <0.002mm.
	D4	20	39.0	40.2	0.25	53.9	
	A3	14	32.1	33.4	0.28	35.1	
	F1	23	70.8	72.2	0.29	75.3	
	F2	15	70.1	70.7	0.30	68.8	
	F3	20	81.6	82.9	0.29	79.7	
	C1	23	42.1	45.0	0.18	68.7	
	C2	15	40.9	43.6	0.26	59.5	
	C3	20	48.9	49.6	0.29	52.0	
	E1	23	40.0	41.2	0.42	26.0	
	E3	20	45.6	46.4	0.26	56.6	
	B2	23	77.9	78.7	0.33	67.4	
	B4	20	58.3	58.9	0.33	62.2	
PR3	C2	20	36.0	37.7	0.32	48.1	Slate from 240m in depth (overburden stress 6.8MPa). Strong foliation, grain size is <0.002mm.
	C3	20	39.4	40.9	0.29	52.4	
	C4	20	37.3	39.6	0.30	47.5	
	B1	25	61.9	63.8	0.30	69.8	
	B2	20	79.0	79.9	0.31	76.4	
	B3	20	72.5	73.6	0.30	73.5	
	E1	23	127.4	128.3	0.26	97.0	
	E2	20	103.1	104.2	0.25	109.3	
	E3	20	96.7	98.0	0.27	84.9	
	F1	23	87.2	90.5	0.25	83.2	
	F3	20	63.8	65.0	0.29	71.6	
	A1	20	49.2	50.6	0.36	49.8	
	A2	20	66.6	67.4	0.29	75.4	
WA sd	A3	65	67.8	75.2	0.13	100.9	Metasediment from 1050m in depth (overburden stress 34.1MPa). Strong foliation. The range of crystal size is from coarse sand to granule.
	As	65	72.5	82.1	0.23	87.0	
	B2	63	81.7	89.9	0.22		
	C1	65	82.7	91.9	0.37	58.7	
	C2	70	78.5	86.0	0.21	89.0	
	D1	45	101.6	107.3	0.34	75.6	
	D3	60	81.7	87.9			

	Ds	50	81.7	88.7	0.30	85.4	
	E2	50	89.4	99.3	0.45	32.3	
WA ou	A4	70	21.7	23.2	0.06	24.0	Ultramafic rock from 1023m in depth (overburden stress 27.7MPa).
	A2	73	30.0	35.4	0.12	27.0	
	B2	49	26.0	30.7	0.18	30.5	
	B3	41	14.2	18.4	0.28	17.8	No visible foliation. The range of crystal size is from very coarse sand to granule.
	B4	35	10.3	14.4	0.17	20.8	
	C2	70	28.4	32.4	0.14	37.9	
	C3	70	29.1	33.4	0.14	34.9	
	C4	72	33.5	38.1	0.14	29.4	
	D2	50	18.5	21.6	0.13	33.2	
	D3	65	20.5	24.1	0.19	19.9	
	D4	65	26.4	31.0			
	E2	75	30.2	34.9	0.08		
	E3	80	33.4	37.2	0.17	44.8	
	E4	70	30.6	34.4	0.31	31.4	
	F2	60	34.4	38.2	0.13	31.7	
	F3	59	20.0	23.7	0.10	30.6	
	F4	58	22.6	25.8	0.08	26.7

Figure 1. The small unloading cycle (white arrow) shows higher modulus than loading cycle while the tangent modulus increases at whole loading process (after [21]).

Figure 2. The 3 main stages in a theoretical volumetric strain curve: crack closure, perfect elastic deformation, and fracture propagation [25].

Figure 3. (a) The cross type strain gauges were glued at the 4 spots shown in the graph. (b) A typical stress path of constant loading/unloading rate (sample CSA C1).

Figure 4. The ultramafic sample WA51 A1. (a) The axial stress-strain/volumetric strain curve. The volumetric strain shows a similar trend as Figure 2. It was shifted to right for illustration purposes. The dash line right next to it is a straight line which could be mistaken as a linear part of the volumetric strain. (b) It shows maximum 26GPa increase in the tangent modulus (black line), before reducing its value and failed. The UCS is 55MPa. The slope of volumetric strain (grey line) increased its value during loading.

Figure 5. The porphyry sample H784d C3. (a) The axial stress-strain/volumetric strain curve. The volumetric strain was shifted to right for illustration purposes. Compared with the dash line (straight line) right next to it, the volumetric strain is slightly bended during loading. (b) The sample shows a less than 2GPa increase in the tangent modulus (black line). The slope of volumetric strain (grey line) slightly increased its value during loading.

Figure 6. The sandstone sample CSA C1. (a) The residual axial strain of 1st cycle is very small (~12 microstrains). The volumetric strain is a straight line. (b) The sample shows a 12GPa decrease in the tangent modulus during 1st loading. The source of decrease is expected to be sliding, because the decrease started at the beginning of loading. The slope of volumetric strain (grey line) is unchanged.

Figure 7. The cartoon graphs show how the compaction phenomenon was formed. First, at the process of extracting core/sample out of underground, the confinement was removed and the crack opened. Second, the core/sample was subjected to a load at the direction of interest. The load leads to the process of crack closure, and in consequence some asperities at the inner crack surface would be crushed. The crack with crushed inner surface may not be able to fully re-open when the applied load is removed; hence the permanent irreversible strain was formed and indistinct from the irreversible strain causing by sliding.

Figure 8. The loading stress-strain curve at 1st and 2nd cycles. σ_m is the maximum stress of 1st and 2nd loading cycles, ϵ_m is the maximum strain of the 1st cycle, ϵ_r is the residual strain of 1st cycle, and $\Delta\epsilon$ is the difference between maximum strain at 1st cycle and 2nd cycle.

Figure 9. The relationship between the portion of residual strain and the increase in secant modulus. Each black dot is the result of each sample. The equation shown at the top of each graph is the linear trend line (black line) of all results. The dash line is the calculated value of $\frac{E_2}{E_1}$ regarding to the value of r shown in each graph.

Figure 10. The relationship between residual strain and the increase in secant modulus from [23] is similar to our results in Figure 9.

Figure 11. The relationship between the portion of residual strain and the increase in secant modulus in all samples.

Table 1

Table 1. Details of the tested rock samples. The samples are orientated in various directions and the overburden stress does not represent the in situ stress level of each sample.

Location and sample ID		Max. applied stress (MPa)	Secant modulus at 1 st cycle (GPa)	Secant modulus at 2 nd cycle (GPa)	Poisson's ratio	Dynamic modulus (GPa)	Comment
FE4	A3	60	46.5	50.9	0.23	59.4	Quartz diorite porphyry complex from 898m in depth, overburden stress 25.7MPa. No visible foliation. The crystal size is coarse sand or very coarse sand.
	A4	67	41.6	46.0	0.20	67.6	
	B1	75	47.0	49.9	0.24	62.5	
	B4	72	48.4	52.8	0.24	64.1	
	C2	61	28.8	32.7	0.28	50.2	
	C3	65	49.4	54.0	0.23	60.3	
	D1	65	35.2	38.8	0.21	55.3	
	D2	60	24.0	27.5	0.31	38.1	
	D4	67	40.9	45.9	0.22	59.7	
	E2	44	32.1	36.9	0.17	58.8	
	E3	56	48.1	52.3	0.24	63.8	
	E4	58	51.5	55.3	0.26	62.7	
	F2	62	27.8	32.9	0.27	51.3	
	F4	50	51.1	56.0	0.20	63.8	
FE5	A2	70	46.5	50.9	0.20	69.9	Quartz diorite porphyry complex from 887m in depth, overburden stress 25.2MPa. No visible foliation. The crystal size is coarse sand with few granule inclusions occasionally.
	A3	68	41.6	46.0	0.19	64.2	
	A4	75	47.0	49.9	0.28	49.5	
	B2	75	48.4	52.8	0.25	65.9	
	B3	35	28.8	32.7	0.15	51.8	
	B4	75	49.8	54.0	0.26	64.3	
	C2	75	41.4	45.8	0.28	63.3	
	C3	60	32.6	37.2	0.26	60.1	
	C4	75	54.8	58.3	0.28	65.5	
	D2	65	30.5	34.4	0.29	62.5	
	D3	75	54.7	57.7	0.27	63.4	
	D4	75	58.9	61.4	0.22	68.6	
	E2	51	51.0	54.7	0.26	64.5	
	E3	75	53.1	56.0	0.20	69.6	
	E4	75	57.2	59.4	0.29	63.6	
	F2	75	49.2	52.8	0.27	64.6	
	F3	65	61.8	64.7	0.16	59.0	
	F4	75	54.2	58.1	0.27	69.0	
WA 45	A1	65	44.8	51.7	0.16	64.2	Metasediment from 1190m in depth, overburden stress 33.7MPa. Strong foliation. The range of crystal size is from coarse sand to granule.
	A2	70	46.2	53.2	0.17	63.5	
	A3	65	58.3	64.6	0.11	77.5	
	B1	70	45.7	50.9	0.12	39.7	
	B3	65	34.7	41.0	0.10	28.8	
	C1	70	38.0	41.9	0.08	50.2	
	C2	65	44.4	48.3	0.08	76.4	
	C3	65	31.4	36.3	0.11	41.6	
	D1	60	40.3	45.8	0.12	52.4	

	D2	69	28.4	37.5	0.06	29.4	
	D3	55	19.6	27.9	0.11	27.5	
	E2	63	33.5	38.2	0.11	47.1	
	E3	56	37.2	43.0	0.10	69.4	
	F1	70	50.7	59.8	0.17	66.0	
	F2	55	24.5	29.0	0.09	37.0	
WA 51	A2	63	98.8	112.0	0.32	118.3	<p>Ultramafic rock from 1206m in depth, overburden stress 39.8MPa.</p> <p>No visible foliation. The range of crystal size is from very coarse sand to granule.</p>
	A3	65	87.8	97.1	0.22	119.2	
	A4	49	89.4	102.3	0.14		
	B1	60	109.0	116.3	0.16	141.4	
	B2	65	110.4	116.7	0.21	131.3	
	B3	60	115.0	125.5	0.18	129.1	
	C1	73	89.3	94.4	0.14	117.9	
	C2	80	137.1	146.0	0.19	149.3	
	C3	65	106.7	113.0	0.15	144.8	
	D1	61	111.1	120.4	0.18	136.1	
	D2	70	108.7	117.0	0.21	128.3	
	E1	73	112.0	116.8	0.19	147.7	
	E2	65	109.6	115.2	0.15	130.3	
	E3	65	130.6	136.6	0.22	142.2	
	F3	70	107.4	115.4	0.15	156.4	
H 782	A1	83	59.3	60.7	0.16	61.1	<p>Porphyry from 1549m in depth, overburden stress 39.6MPa.</p> <p>No visible foliation. The range of crystal size is from medium sand to granule.</p>
	A2	90	60.0	60.8	0.18	67.3	
	A3	102	58.9	60.2	0.17	56.0	
	B1	90	65.6	66.9	0.17	63.7	
	B3	81	51.7	53.4	0.19	56.8	
	B4	100	53.8	55.3	0.14	56.7	
	C1	90	63.4	64.6	0.17	65.2	
	C2	83	67.2	68.2	0.15	70.0	
	C4	90	58.8	60.2	0.23	62.1	
	D1	95	59.7	60.5	0.20	68.1	
	D2	90	56.1	57.3	0.20	64.4	
	D4	90	60.0	61.4	0.16	62.8	
	E1	85	61.4	62.3	0.20	65.3	
	E2	83	53.2	54.4	0.19	60.9	
	E3	90	58.6	59.7	0.23	61.2	
	F1	90	64.6	65.3	0.22	67.8	
	F3	90	61.3	62.7	0.21	64.3	
H 784s	A2	80	38.3	40.0	0.13	47.4	<p>Porphyry from 1614m in depth, overburden stress 40.2MPa.</p> <p>No visible foliation. The crystal size is generally less than 2mm with few granule inclusions occasionally.</p>
	A4	95	41.9	43.4	0.16	46.2	
	A5	75	74.4	75.6	0.12	54.7	
	B1	95	40.6	42.0	0.21	46.3	
	B2	74	72.6	74.6	0.14	72.6	
	B4	66	37.6	39.1	0.13	45.0	
	C2	80	36.8	38.9	0.18	42.8	
	C3	70	48.8	50.0	0.19	48.0	
	C4	90	39.3	41.3	0.19	45.0	
	D2	85	36.4	39.4	0.19	41.7	

	D3	86	44.4	45.7	0.19	46.9	
	E1	90	45.7	46.9	0.19	45.3	
	E2	65	37.0	38.7	0.14	38.0	
	E3	70	26.8	28.7	0.17	33.8	
	F1	95	41.4	41.0	0.18	50.2	
	F2	85	39.8	41.3	0.23	45.8	
	F3	75	38.0	39.7	0.18	34.7	
H 784d	A2	85	61.2	62.0	0.20	55.5	<p>Porphyry from 1637m in depth, overburden stress 42.5MPa.</p> <p>No visible foliation. The crystal size is generally less than 2mm with few granule inclusions occasionally.</p>
	A3	82	65.7	66.6	0.22	64.2	
	A5	85	60.5	61.4	0.19	54.4	
	B2	80	56.0	57.4	0.19	60.0	
	B3	80	62.2	63.3	0.21	68.8	
	B4	80	60.6	61.7	0.20	61.3	
	C1	85	65.9	66.9	0.19	67.6	
	C3	55	62.8	63.9	0.18	70.1	
	C4	85	64.9	66.0	0.21	62.5	
	D1	80	61.1	62.2	0.21	64.4	
	D2	78	67.8	68.8	0.19	65.5	
	D3	77	71.2	72.2	0.16	72.0	
	E1	80	61.4	62.9	0.13	70.1	
	E3	80	61.6	62.8	0.20	69.0	
	E4	65	64.5	65.7	0.19	64.2	
	F1	70	53.8	55.2	0.17	60.9	
	F3	80	64.3	65.4	0.22	62.4	
	F4	90	59.2	60.2	0.20	67.3	
FL	A1	45	35.3	42.5	0.20	66.0	<p>Pegmatitic granite from 320m in depth, overburden stress 8.5MPa.</p> <p>No visible foliation. The crystal size is generally between 1-4mm, with occasionally large inclusions (>5mm).</p>
	A3	45	50.9	54.5	0.37	46.0	
	B1	46	73.6	77.0	0.19	90.0	
	B2	45	62.8	64.4	0.23	77.3	
	B3	45	45.8	46.4	0.18	66.5	
	C2	45	57.2	61.5	0.16	83.4	
	C3	45	59.0	62.4	0.20	68.1	
	D1	45	58.8	61.5	0.35	49.2	
	D2	45	39.9	43.9	0.40	34.2	
	D3	45	53.4	57.1	0.45	23.6	
	E1	46	74.1	76.8	0.39	57.3	
	E2	45	43.6	47.3	0.30	61.0	
	E3	45	37.6	39.5	0.34	49.4	
	F1	45	61.5	65.1	0.37	50.6	
	F2	45	42.7	45.0	0.38	44.7	
	F3	45	49.7	53.2	0.38	45.7	
CSA	A1	100	63.0	64.5	0.26	53.8	<p>Sandstone from 1531m in depth, overburden stress 43MPa.</p> <p>No visible foliation. The range of grain size is from coarse silt to very fine sand.</p>
	A3	95	59.6	61.9	0.28	54.2	
	A4	70	70.6	72.6	0.22	66.7	
	B1	110	73.2	75.5	0.30	80.1	
	B2	94	90.6	91.9	0.23	90.9	
	B3	90	88.7	89.8	0.22	92.6	
	C1	90	81.0	81.9	0.23	86.4	

	C3	95	79.3	79.8	0.24	82.4	
	C4	90	80.1	81.1	0.25	84.5	
	D2	76	79.8	82.1	0.26	84.8	
	D3	70	83.0	84.1	0.24	85.3	
	E1	75	90.8	90.8	0.20	95.1	
	E2	90	88.7	90.1	0.22	86.9	
	E3	90	87.4	88.5	0.20	91.9	
	F1	110	76.7	78.4	0.23	76.2	
	F3	95	72.7	74.2	0.25	73.9	
PR2	D1	23	41.4	42.5	0.31	52.5	Slate from 170m in depth, overburden stress 4.8MPa. Strong foliation, grain size is <0.002mm.
	D4	20	39.0	40.2	0.25	53.9	
	A3	14	32.1	33.4	0.28	35.1	
	F1	23	70.8	72.2	0.29	75.3	
	F2	15	70.1	70.7	0.30	68.8	
	F3	20	81.6	82.9	0.29	79.7	
	C1	23	42.1	45.0	0.18	68.7	
	C2	15	40.9	43.6	0.26	59.5	
	C3	20	48.9	49.6	0.29	52.0	
	E1	23	40.0	41.2	0.42	26.0	
	E3	20	45.6	46.4	0.26	56.6	
	B2	23	77.9	78.7	0.33	67.4	
	B4	20	58.3	58.9	0.33	62.2	
PR3	C2	20	36.0	37.7	0.32	48.1	Slate from 240m in depth, overburden stress 6.8MPa. Strong foliation, grain size is <0.002mm.
	C3	20	39.4	40.9	0.29	52.4	
	C4	20	37.3	39.6	0.30	47.5	
	B1	25	61.9	63.8	0.30	69.8	
	B2	20	79.0	79.9	0.31	76.4	
	B3	20	72.5	73.6	0.30	73.5	
	E1	23	127.4	128.3	0.26	97.0	
	E2	20	103.1	104.2	0.25	109.3	
	E3	20	96.7	98.0	0.27	84.9	
	F1	23	87.2	90.5	0.25	83.2	
	F3	20	63.8	65.0	0.29	71.6	
	A1	20	49.2	50.6	0.36	49.8	
	A2	20	66.6	67.4	0.29	75.4	
WA sd	A3	65	67.8	75.2	0.13	100.9	Metasediment from 1050m in depth, overburden stress 34.1MPa. Strong foliation. The range of crystal size is from coarse sand to granule.
	As	65	72.5	82.1	0.23	87.0	
	B2	63	81.7	89.9	0.22		
	C1	65	82.7	91.9	0.37	58.7	
	C2	70	78.5	86.0	0.21	89.0	
	D1	45	101.6	107.3	0.34	75.6	
	D3	60	81.7	87.9			
	Ds	50	81.7	88.7	0.30	85.4	
	E2	50	89.4	99.3	0.45	32.3	
WA ou	A4	70	21.7	23.2	0.06	24.0	Ultramafic rock from 1023m in depth, overburden stress 27.7MPa.
	A2	73	30.0	35.4	0.12	27.0	
	B2	49	26.0	30.7	0.18	30.5	
	B3	41	14.2	18.4	0.28	17.8	

	B4	35	10.3	14.4	0.17	20.8	No visible foliation. The range of crystal size is from very coarse sand to granule.
	C2	70	28.4	32.4	0.14	37.9	
	C3	70	29.1	33.4	0.14	34.9	
	C4	72	33.5	38.1	0.14	29.4	
	D2	50	18.5	21.6	0.13	33.2	
	D3	65	20.5	24.1	0.19	19.9	
	D4	65	26.4	31.0			
	E2	75	30.2	34.9	0.08		
	E3	80	33.4	37.2	0.17	44.8	
	E4	70	30.6	34.4	0.31	31.4	
	F2	60	34.4	38.2	0.13	31.7	
	F3	59	20.0	23.7	0.10	30.6	
	F4	58	22.6	25.8	0.08	26.7	

Figure 3

Figure 4

Figure 5

Figure 6

Figure 8

Figure 9

Figure 10

Figure 11