Geomechanics and Engineering, *Vol. 14, No. 2 (2018) 203-209*
DOI: https://doi.org/10.12989/gae.2018.14.2.203

Experimental study of Kaiser effect under cyclic compression and tension tests

Yulong Chen[1] and Muhammad Irfan*[2]

[1]*Department of Hydraulic Engineering, Tsinghua University, China*
[2]*Civil Engineering Department, University of Engineering and Technology Lahore, Pakistan*

(Received August 25, 2016, Revised July 9, 2017, Accepted July 14, 2017)

Abstract. Reliable estimation of compressive as well as tensile in-situ stresses is critical in the design and analysis of underground structures and openings in rocks. Kaiser effect technique, which uses acoustic emission from rock specimens under cyclic load, is well established for the estimation of in-situ compressive stresses. This paper investigates the Kaiser effect on marble specimens under cyclic uniaxial compressive as well as cyclic uniaxial tensile conditions. The tensile behavior was studied by means of Brazilian tests. Each specimen was tested by applying the load in four loading cycles having magnitudes of 40%, 60%, 80% and 100% of the peak stress. The experimental results confirm the presence of Kaiser effect in marble specimens under both compressive and tensile loading conditions. Kaiser effect was found to be more dominant in the first two loading cycles and started disappearing as the applied stress approached the peak stress, where felicity effect became dominant instead. This behavior was observed to be consistent under both compressive and tensile loading conditions and can be applied for the estimation of in-situ rock stresses as a function of peak rock stress. At a micromechanical level, Kaiser effect is evident when the pre-existing stress is smaller than the crack damage stress and ambiguous when pre-existing stress exceeds the crack damage stress. Upon reaching the crack damage stress, the cracks begin to propagate and coalesce in an unstable manner. Hence acoustic emission observations through Kaiser effect analysis can help to estimate the crack damage stresses reliably thereby improving the efficiency of design parameters.

Keywords: acoustic emission (AE); Kaiser effect; marble; cyclic uniaxial compressive test; cyclic Brazilian test

1. Introduction

Acoustic emission (AE) technique is among the modern physical techniques for the determination of in-situ rock stresses. Acoustic emissions developed in a rock sample upon loading are characteristic of its nature. As a general principle, AE activity is zero or close to background level when the magnitude of stress in the subsequent loading cycle remain less than the previously attained peak. Thus this technique can effectively be used to estimate the in-situ stress of rock samples. This phenomenon was first discovered by Kaiser (1953), and hence termed as Kaiser effect. Subsequent to Kaiser, who observed this phenomenon in metals, its existence was further confirmed in rocks by Goodman (1963).

Considering the low cost and robustness of AE method compared to other in-situ testing methods, it has gained popularity particularly the last two decades (Tuncay and Ulusay 2008). When applying Kaiser effect for the determination of geo-stresses, laboratory testing is typically conducted in uniaxial compression settings (Filimonov *et al.* 2001, Seto *et al.* 1999, Villaescusa *et al.* 2002). As a matter of fact, geological history imposed to rocks is rather complex and includes not only compressive stress state but also tensile stress state. For the safe design and construction of underground structures, determination of in-situ stresses not only in compression but also in tension is essential. In countries with high seismic activities, it is indispensable to determine the in situ tensile stress of rock caused by vibrations. Tensile stress usually occurs in rock around large, internally pressurized or complex shaped caverns (Hashiba and Fukui 2015, Nian *et al.* 2017).

Hence tensile type of experiments are needed to be performed to better understand the mechanism of AE in rocks. A lot of research, both theoretical and experimental, has been conducted exploring the tensile strength of rocks by means of Brazilian tests (Andreev, 1991a, b, Erarslan and Williams 2012, Fairhurst 1964, Khanlari *et al.* 2014, Lanaro *et al.* 2009, Li and Wong 2013, Mikl-Resch *et al.* 2015, Saksala *et al.* 2013, Wu *et al.* 2015). However, little attention has been paid for the determination of in-situ stresses through this test. Hence the Kaiser effect in rocks under tensile loading conditions, is rather unexplored. Although the role of tensile stresses in the formation of stress memory is recognized in literature (Fu *et al.* 2015), yet limited practical evidence of this phenomenon is available.

Efficient design and analysis of underground excavations is not possible without reliable evaluation of rock stresses in the in-situ state (Seto *et al.* 1997). Present study aims to explore the Kaiser effect in marble both in compressive, and tensile stress state. Cyclic uniaxial compressive tests were used to explore the behavior in

*Corresponding author, Assistant Professor
E-mail: mirfan1@msn.com

ISSN: 2005-307X (Print), 2092-6219 (Online)

compression, while cyclic Brazilian tests were performed to study the phenomenon in tensile stress state. A continuous record of AE activity was recorded for the evaluation of Kaiser effect. The results of this study will further the understanding and characterization of AE in marble under cyclic uniaxial compressive and Brazilian tests. They will also provide a reference for determining in-situ stresses of rocks which are an integral component in evaluating the stability and performance of underground structures.

2. Experimental materials and methods

2.1 Specimen preparation

One of the main problems in laboratory investigation of Kaiser effect is the influence of in-situ stress memory on the test specimens. Specimens in this study were thus taken from a quarry near the Earth's surface. Hence the recent stresses in this rock were negligible, or at least, by far smaller than the stresses applied during laboratory testing program.

A massive intact marble block, pure white in color and uniform texture having no visible defects, was collected from the site. Standard procedures of incision and polishing were followed for the processing of rock cores. Cylindrical specimens of ϕ50 mm×100 mm for uniaxial compressive tests, and discs of ϕ50 mm×25 mm for Brazilian tests were then formed. The ends of samples were polished and smoothened to remove asperities which would have been source of acoustic noise leading to misinterpretation of Kaiser effect. The physical and strength properties of marble used in this study are given in Table 1.

The predominant mineral determined using the X-ray diffraction (XRD) technique in marble was calcite which accounted for over 95% of the total volume with some interior reflective crystals. The marble specimen contained a single mineral constituent, with particles appearing to be quite fine, homogeneous and compactly arranged as evident from petrographical study (Fig. 1). These microstructural features provide micro-mechanical foundation for the analysis of the AE characteristics presented later in this paper.

Table 1 Physical and strength properties of marble

Density (g/cm^3)	Porosity (%)	Young's modulus (GPa)	Poisson's ratio	Compressive strength (MPa)	Brazilian strength (MPa)
2.699	0.744	27	0.35	80.7	7.1

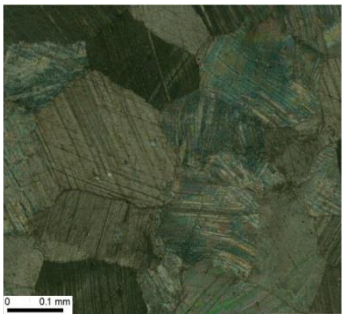


Fig. 1 Results of petrographical study shown in the form of a thin-section image of marble

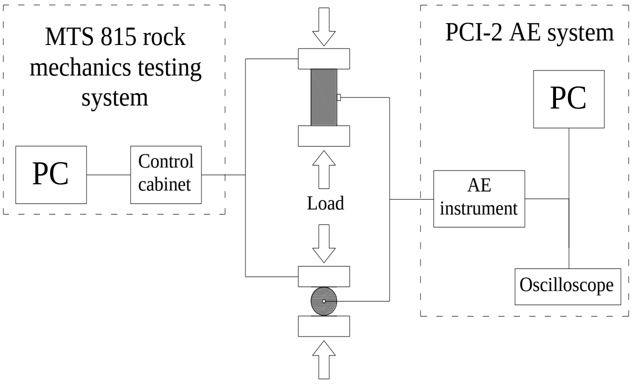


Fig. 2 Schematic illustration of the testing equipment

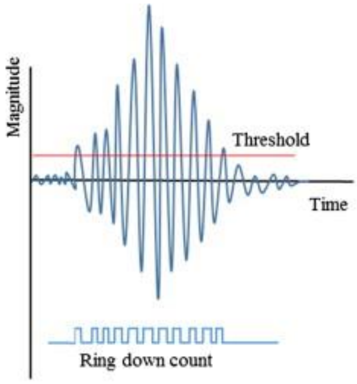


Fig. 3 Typical characteristics of an AE signal (Mao and Towhata 2015)

Table 2 Peak stresses applied in each loading cycle

	Cycle	1st	2nd	3rd
Peak stress (MPa)	Uniaxial compression	32.2	48.4	64.5
	Brazilian test	2.8	4.2	5.6

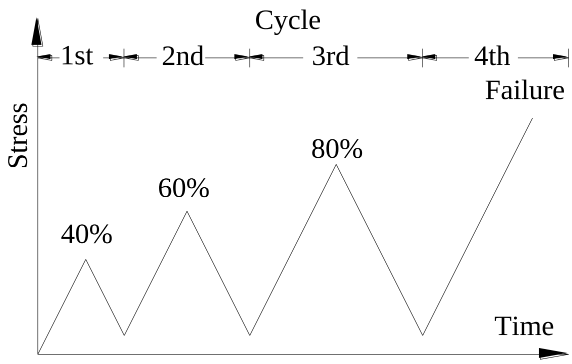


Fig. 4 Loading paths for cyclic uniaxial compressive and Brazilian tests

2.2 Testing equipment

The testing equipment comprised of MTS 815 Flex Test GT rock mechanics testing machine. The machine was operated through a digital computer connected to an automatic control system. For the determination of AE activity, PCI-2 AE system with an operating frequency of 1 kHz-3 MHz and an 18 bit A/D resolution was used. The whole assembly is schematically illustrated in Fig. 2.

Real-time monitoring of stresses and strains was made possible by means of digital data acquisition system attached to MTS 815 rock testing system. The AE sensor used for the experiment was Mic30 sensor having a central frequency of 300 kHz, and an operating frequency ranging from 150 kHz to 1000 kHz. Gain of the preamplifier was 40 dB, and the threshold was fixed at 30 dB.

The AE system comprised of AE sensor, preamplifier, data acquisition, processing, and recording units. The AE sensor was attached to the specimen by means of elastic bands. In order to facilitate the contact between AE sensor and surface of the specimen, petroleum jelly was applied between them. The purpose of AE sensors which were placed in contact with sample being monitored was to detect motion of stress waves. The propagation of stress wave induced a local dynamic material displacement in the specimen. The AE sensors converted the low displacement and high frequency wave into electrical signals. The stress wave, upon reaching the surface of marble specimen, induced a small deformation at the surface. The piezoelectric ceramics of AE sensors got stressed due to particle oscillation at the surface of specimen. In return to the recorded oscillations, the AE sensors produced a current. The produced electrical signal was amplified through the pre-amplifier, processed and then recorded by the signal recording unit.

The parameters used in this research for studying the AE are AE count rate and cumulative AE counts. The development of AE activity from crack initiation and propagation was appraised through *ring down counts*, defined as the number of times the magnitude of AE signal crosses the preset threshold (Mao and Towhata 2015). *AE count rate* corresponds to the number of AE signals per second and the *cumulative AE counts* refers to the total number of AE signals received from the beginning of the test to a certain instant. Fig. 3 illustrates a typical waveform of an AE event.

2.3 Testing method

Four tests each, were performed for cyclic uniaxial compressive and Brazilian tests. A similar loading path was used for each type of test. Fig. 4 presents the loading path used in this study. It consists of four cycles of loading and unloading. Loading control with a rate of 0.1MPa/s was used for both loading and unloading. In each cycle, the unloading boundary was set to 1 MPa in order to maintain contact between the rock specimen and loading platens. The peak stress at the 1st, 2nd, and 3rd cycles was kept to approximate 40%, 60%, and 80% of peak strength, respectively. The peak stresses for cyclic uniaxial compressive and Brazilian tests in 1st, 2nd, and 3rd loading cycles are given in Table 2. In the 4th cycle, the stress was continuously applied until specimen failure. The test was finished at the completion of 4th reloading cycle.

3. Experimental results

3.1 Analysis of cyclic uniaxial compressive tests

Four specimens, numbered U1~U4, have been tested in cyclic uniaxial compression. Test results of each specimen are listed in Table 3. Typical test results (i.e., U1 and U3) are analyzed further to reveal the role of Kaiser effect. The evolution curves of stress and accompanied AE count rate are presented in Fig. 5. In each plot of Fig. 5, the hollow squares represent the stress value at which AE events are observed again. The respective values of felicity ratios *(FR)* are also displayed at each loading cycle. Felicity ratio (*FR*), is a measure of magnitude of stress in each subsequent cycle at which AE is reinitiated. It is mathematically given as

Table 3 Summary of results from cyclic uniaxial compressive and Brazilian tests

Test condition	Specimen No.	Peak strength (MPa)	*FR* in each cycle		
			2nd	3rd	4th
Cyclic Uniaxial Compression	U1	80.8	1.06	1.03	0.95
	U2	80.1	1.05	1.01	0.96
	U3	79.6	1.02	0.98	0.94
	U4	82.3	1.07	1.00	0.92
Cyclic Brazilian Test	B1	7.2	1.05	1.02	0.98
	B2	6.9	1.04	0.98	0.96
	B3	6.8	1.02	0.98	0.94
	B4	7.4	1.07	1.05	0.95

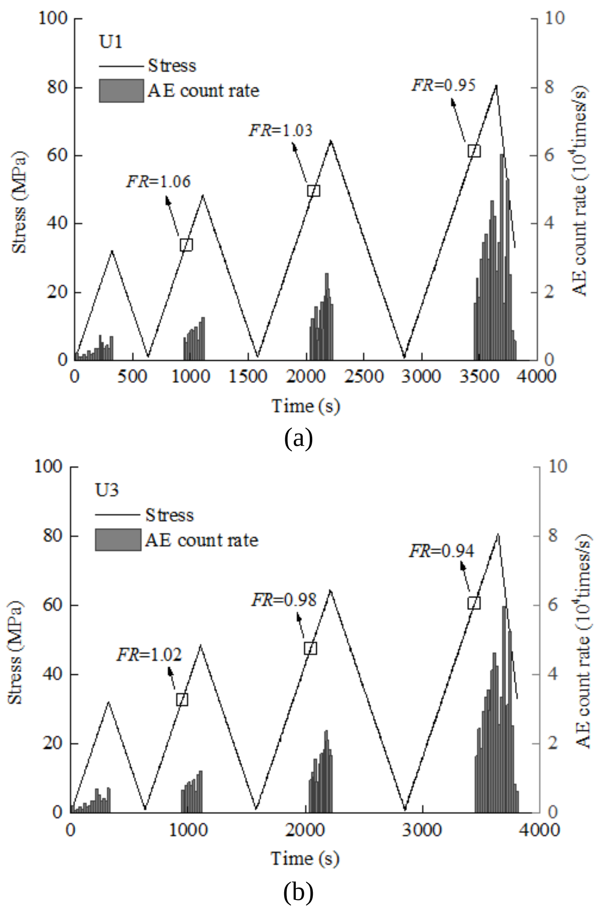
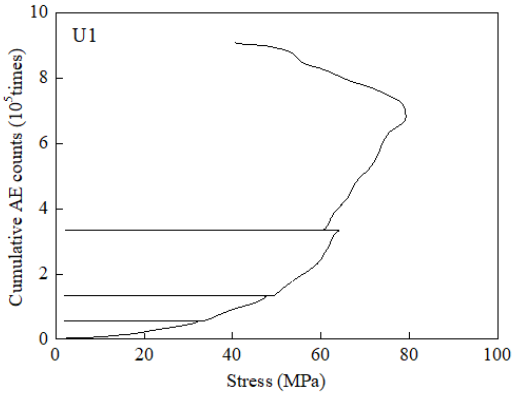


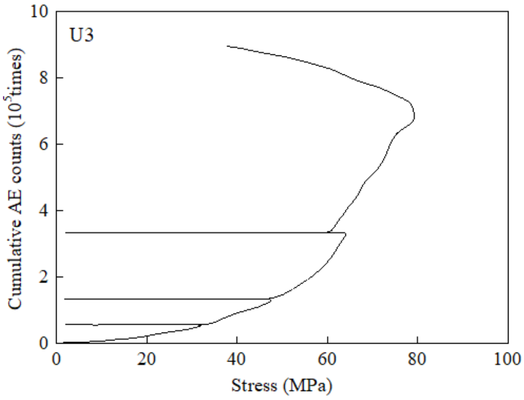
Fig. 5 Relationship for stress-time-AE count rate of marble specimens subjected to cyclic uniaxial compressive tests

$$Felicity\ ratio\ (FR) = \frac{Stress\ at\ onset\ of\ \ AE}{Previous\ maximum\ stress} \quad (1)$$

It can be seen from Fig. 5 that the AE activities generated in response to applied stress are observed predominantly during the loading phases only. Even at low load, the specimen exhibited distinct AE characteristics. Also, some microcracks and AE events were still generated after the attainment of peak stress. By contrast, no AE is observed during unloading phases or in the subsequent reloading phases prior to attainment of previous maximum stress. This shows that no microcracking occurred during unloading or the subsequent reloading, before the previous maximum stress is exceeded. These observations confirm the existence of Kaiser effect in rocks.



(a)



(b)

Fig. 6 Cumulative AE counts plotted against successive loading-unloading cycles of stress in uniaxial compression test

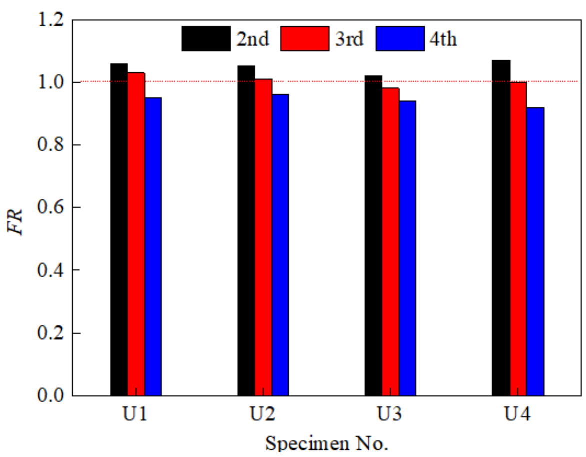


Fig. 7 Comparison of FR in different cycles of cyclic uniaxial compressive tests

Significant AE events took place in reloading phase when the load approaches the peak load of the previous load cycle. For the 1st loading cycle of sample U1, the maximum stress reached was 32.2 MPa. Subsequently, in the 2nd loading cycle, distinct AE events reappear when the reloading stress reached approximately 33.85 MPa. The stress value at the Kaiser point is 1.06 times that of previous loading stress and thereby the corresponding *FR* is also 1.06. In the succeeding 3rd cycle, the *FR* decreases to 1.03 which further decreased to 0.95 in the last cycle. *FR* values of all the tested specimens are summarized in Table 3.

It is noted that the onset of AE activities in the reloading phases does not always occur when the reload exceeds the maximum stress level. Observation is made that the AE activities may restart prior to previous maximum stress, particularly when the experienced stress level is relatively high, i.e., close to the peak strength of specimen. This observation breaches the Kaiser effect theory (i.e., FR less than 1.0). This, alternatively, leads to the production of Felicity effect during reloading phases.

For the Kaiser effect investigations, relationship showing cumulative AE counts versus the stress is more common since it facilitates in distinguishing the Kaiser effect level. The trend of cumulative AE counts plotted against stress during four cycles of uniaxial compression for specimens U1 and U3 are shown in Fig. 6. The horizontal lines in these plots represent partial unloading and reloading of the specimen at various stress levels. It is pertinent to note that there is no acoustic emission during unloading and reloading until the magnitude of stress in the previous loading cycle is reached. Thereon with continuous increase in loading, AE goes on increasing. Although in most cases inflexion occurs as the peak stress of the previous loading cycle is surpassed, an early onset of AE, ahead of previous maximum stress is also observed in some cases. Such observation was made at high stress values, particularly close to peak stress.

Fig. 7 shows the FR values in the following three cycles. A similar trend of *FR* was observed for all the tests under cyclic uniaxial compression conditions. The *FR* values show a continuously decreasing tendency. *FR* is always observed to be larger than 1.0 in 2nd cycle. However, *FR* tend to be less than 1.0 showing the presence of Felicity effect in some of the 3rd and all of the 4th cycles.

3.2 Analysis of cyclic Brazilian tests

Performance of Brazilian test involves application of compressive force diametrically on a specimen disk, which in-turn splits down in tension. Tensile strength thus obtained is an indirect measure of diametrically loaded compressive strength. Load application in this manner leads to localized compressive stresses under the loaded section which gradually disappear away from the loaded section. By contrast, tensile stresses are distributed in the center of the

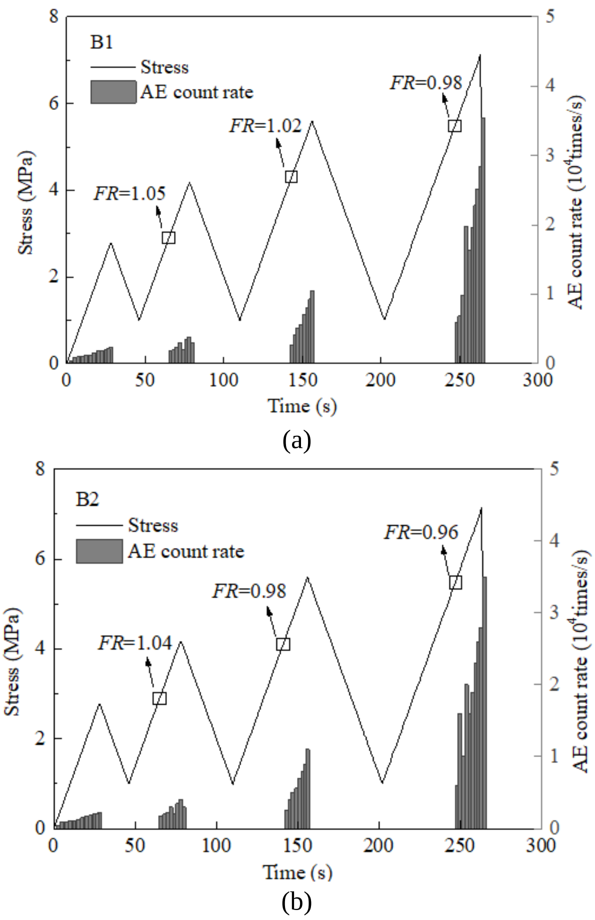


Fig. 8 Relationship for stress-time-AE count rate of marble specimens subjected to cyclic Brazilian tests

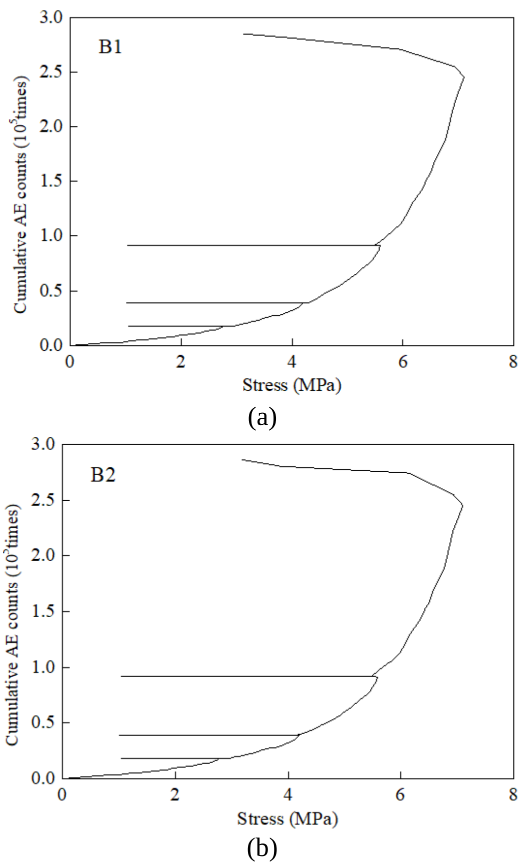


Fig. 9 Cumulative AE counts versus stress in four successive cycles of Brazilian test

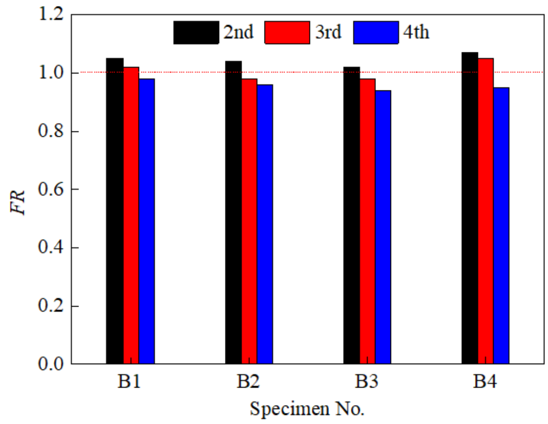


Fig. 10 The change of FR with cycle under cyclic Brazilian tests

disk (Erarslan and Williams 2012, Yuan and Shen 2017). Moreover, no AE event is observed around the loaded section because of the end restraint effect to the rock specimen (Liu *et al.* 2014). Therefore, during Brazilian tests, cracking is primarily caused by tensile stresses solely, which ultimately leading to failure.

The cyclic Brazilian tests included in this paper have been carried out on four specimens captioned B1-B4. The test results are summarized in Table 3. The relationship curves for stress-time-AE count rate for typical specimens B1 and B2 under cyclic Brazilian test are shown in Fig. 8. Similar to cyclic uniaxial compression, the Kaiser effect is obvious in most cases. The activity of AE is absent during unloading and preliminary reloading phases. For example, for the 2^{nd} cycle of sample B1, the AE events reappear when the loading stress becomes 2.90 MPa, whereas the previous largest stress was 2.8 MPa. Hence, the Kaiser effect exists in the cyclic Brazilian tests. This finding from cyclic Brazilian test is identical to the observations made in cyclic uniaxial compressive test. This confirms the validity of Kaiser effect in determination of in situ stresses by Brazilian test. For sample B1, the *FR* is found to be 1.05 in the 2^{nd} cycle and decreases to 1.02 in the 3rd cycle and to 0.98 in the 4^{th} cycle. For specimen B2, the *FR* is 1.04 in the 2nd cycle, which then decreases to 0.98 and 0.96 in the 3rd and 4th cycle, respectively. It is worth noting that the *FR* value in Brazilian tests decreases in each subsequent loading cycle. An *FR* value of less than unity indicates the specimen to be approaching its peak stress level. The Kaiser effect and the associated *FR* can thus be useful in establishing the stress history of rock and the possible peak strength of rocks.

The accumulative AE counts of the entire four loading cycles resulting from cyclic Brazilian tests are plotted against stress in Fig. 9. It is seen that the Kaiser effect is apparent except in the last reloading cycle, and in some cases of the 3^{rd} cycle. The evolution of *FR* during all loading processes for cyclic Brazilian tests are summarized in Fig. 10. *FR* values exhibit a decreasing trend. An *FR* value of greater than 1.0 indicates the presence of Kaiser effect. *FR* of the tested specimen is found to be greater than 1.0 in all the 2nd loading cycles and some of the 3rd loading cycles. *FR* was observed to be less than 1.0 in the 4th loading cycle of all the tests. The Kaiser effect, thus, diminishes at high stress levels in rocks, which is consistent with the result from cyclic uniaxial compressive test as mentioned in previous section.

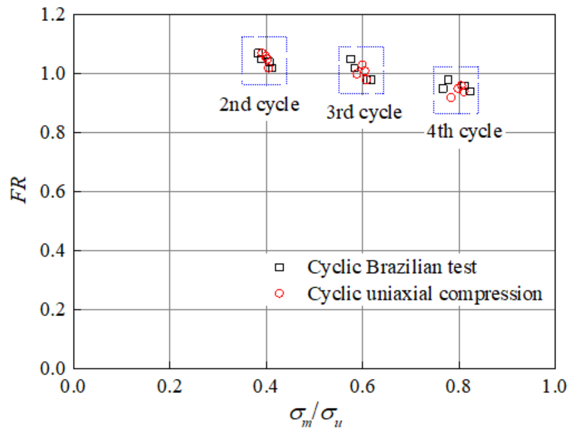


Fig. 11 Variation of FR with maximum pre-stress

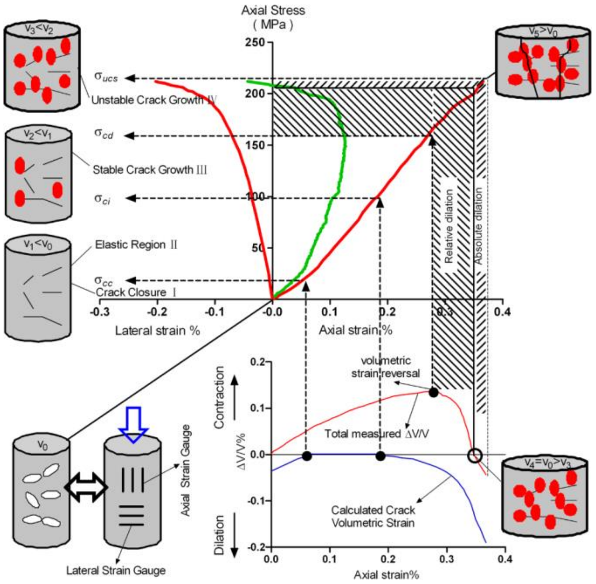


Fig. 12 Stress-strain diagram showing different stages of crack development during a uniaxial compressive test (Xue *et al.* 2014)

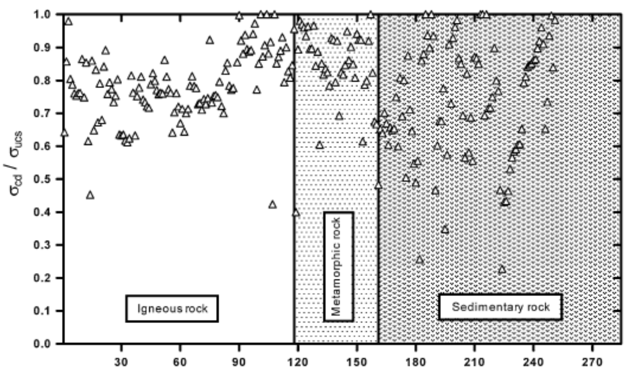


Fig. 13 Ratio σ_{cd}/σ_{ucs} for different rocks (Xue *et al.* 2014)

4. Discussion

The FR is used as a quantitative measure of the magnitude of the previous peak stress and the effectiveness of Kaiser effect. The FR is expected to be 1.0 due to Kaiser effect. However, Kaiser effect degrades when the peak stress is approached. Under such conditions felicity effect dominates.

Kaiser effect level is certainly rock-dependent (Lavrov 2003). Fig. 11 shows the dependency of the FR on the maximum pre-stress for both cyclic uniaxial compressive and Brazilian tests, where σ_m is the maximum pre-stress and σ_u is the ultimate strength for uniaxial compressive or Brazilian tests. The experimental results from cyclic uniaxial compressive and Brazilian tests consistently show that FR decreases as pre-stress increases. The behavior of marble specimen transitions from Kaiser effect to Felicity effect when the maximum pre-stress is around 60% of ultimate strength ($\sigma_m/\sigma_u \approx 0.6$). Kaiser effect disappear completely when maximum pre-stress becomes around 80% of peak stress.

Li and Nordlund (1993) attributed the distorted Kaiser effect to the development of new cracks which generate continuous bursts of AE. If during a loading cycle the crack is stable and does not develop further without further increase in load, during the reloading cycle Kaiser effect would show up. If the crack becomes unstable at a certain load level and continues to propagate without further increase in load, AE in the reloading cycle would appear at a lower stress level than the previously attained peak stress hence giving rise to felicity effect.

Kurita and Fujii (1979) attributed the Kaiser effect to the dilatancy behavior of the specimens. They found the Kaiser effect to disappear when the dilatancy threshold is exceeded by the previous maximum stress. If the previous stress is higher than the onset of dilatancy, it can create sufficient amount of cracks which can change the stress path and rock structure in the following loading cycle. Hence causing AE to start at much earlier than the previous maximum stress (Hsieh *et al.* 2015).

The crack damage stress, σ_{cd}, corresponds to the axial deviatoric stress where the volumetric deformation of the specimen switches from compaction-dominated to dilatancy-dominated (Yang *et al.* 2015). Moreover, σ_{cd} is the turning point between the stable crack growth stage and the unstable crack growth stage where cracks begin to propagate and coalesce with one another in an unstable manner. This behavior is schematically represented in Fig. 12.

Xue *et al.* (2014) compiled the crack damage stress of different rock types from the available literature based on uniaxial compressive tests. They plotted the ratios of σ_{cd}/σ_{ucs} for all the data sets as shown in Fig. 13. From Fig. 13, the σ_{cd}/σ_{ucs} for metamorphic rock generally ranges between 0.60 and 0.97 with a median of around 0.85. Considering the median value of around 0.85 as a reference, the behavior of marble specimens should change from Kaiser effect to Felicity effect when the maximum applied stress is around 85% of ultimate stress. Marbles as metamorphic rock used in this study consistently follow this relationship. The 2nd and 3rd cycle peak loads in this study are equivalent to 60% and 80% of peak strength, respectively, which is large enough to surpass the crack damage threshold, contributing to the presence of Felicity effect.

5. Conclusions

The performance of Kaiser effect in marble are examined under cyclic uniaxial compressive and Brazilian tests. On the basis of these observations and analyses of AE monitoring results, the following conclusions are drawn:

• Kaiser effect in marble from cyclic uniaxial compressive and Brazilian tests is obvious when the preexisting stress is smaller than the crack damage stress and becomes ambiguous when the pre-stress exceeds the crack damage stress followed by unstable crack growth.

• The pre-stress closer to the ultimate strength, results in less-pronounced Kaiser effect during reloading. This is indicated with a decrease in *FR* with increasing pre-stress.

The existence of Kaiser effect for marble evaluated through cyclic uniaxial compressive and Brazilian tests has been validated, and its performance has been tested in this study. The findings of this research confirm Brazilian test as a reliable means for Kaiser effect investigations.

Acknowledgments

This study was financially supported by China Postdoctoral Science Foundation (2017M620048).

References

Andreev, G. (1991a), "A review of the Brazilian test for rock tensile strength determination. Part I: Calculation formula", *Min. Sci. Technol.*, **13**(3), 445-456.

Andreev, G. (1991b), "A review of the Brazilian test for rock tensile strength determination. Part II: Contact conditions", *Min. Sci. Technol.*, **13**(3), 457-465.

Erarslan, N. and Williams, D.J. (2012), "Experimental, numerical and analytical studies on tensile strength of rocks", *J. Rock. Mech. Min. Sci.*, **49**, 21-30.

Fairhurst, C. (1964), "On the validity of the 'Brazilian' test for brittle materials", *Rock Mech. Min. Sci. Geomech. Abstr.*, **1**(4), 535-546.

Filimonov, Y.L., Lavrov, A., Shafarenko, Y. and Shkuratnik, V. (2001), "Memory effects in rock salt under triaxial stress state and their use for stress measurement in a rock mass", *Rock Mech. Rock Eng.*, **34**(4), 275-291.

Fu, X., Xie, Q. and Liang, L. (2015), "Comparison of the Kaiser effect in marble under tensile stresses between the Brazilian and bending tests", *Bull. Eng. Geol. Environ.*, **74**(2), 535-543.

Goodman, R.E. (1963), "Subaudible noise during compression of rocks", *Geol. Soc. Am. Bull.*, **74**(4), 487-490.

Hashiba, K. and Fukui, K. (2015), "Effect of water on the deformation and failure of rock in uniaxial tension", *Rock Mech. Rock Eng.*, **48**(5), 1751-1761.

Hsieh, A., Dight, P. and Dyskin, A. (2015), "The rock stress memory unrecoverable by the Kaiser effect method", *J. Rock. Mech. Min. Sci.*, (75), 190-195.

Kaiser, J. (1953), "Erkenntnisse und folgerungen aus der messung von geräuschen bei zugbeanspruchung von metallischen werkstoffen", *Steel Res.*, **24**(1-2), 43-45.

Khanlari, G.R., Heidari, M., Sepahigero, A.A. and Fereidooni, D. (2014), "Quantification of strength anisotropy of metamorphic rocks of the Hamedan province, Iran, as determined from cylindrical punch, point load and Brazilian tests", *Eng. Geol.*, **169**, 80-90.

Kurita, K. and Fujii, N. (1979), "Stress memory of crystalline rocks in acoustic emission", *Geophys. Res. Lett.*, **6**(1), 9-12.

Lanaro, F., Sato, T. and Stephansson, O. (2009), "Microcrack modelling of Brazilian tensile tests with the boundary element method", *J. Rock. Mech. Min. Sci.*, **46**(3), 450-461.

Lavrov, A. (2003), "The Kaiser effect in rocks: Principles and stress estimation techniques", *J. Rock. Mech. Min. Sci.*, **40**(2), 151-171.

Li, C. and Nordlund, E. (1993), "Experimental verification of the Kaiser effect in rocks", *Rock Mech. Rock Eng.*, **26**(4), 333-351.

Li, D. and Wong, L.N.Y. (2013), "The Brazilian disc test for rock mechanics applications: Review and new insights", *Rock Mech. Rock Eng.*, **46**(2), 269-287.

Liu, J., Chen, L., Wang, C., Man, K., Wang, L., Wang, J. and Su, R. (2014), "Characterizing the mechanical tensile behavior of Beishan granite with different experimental methods", *J. Rock. Mech. Min. Sci.*, **69**, 50-58.

Mao, W. and Towhata, I. (2015), "Monitoring of single-particle fragmentation process under static loading using acoustic emission", *Appl. Acoust.*, **94**, 39-45.

Mikl-Resch, M.J., Antretter, T., Gimpel, M., Kargl, H., Pittino, G., Tichy, R., Ecker, W. and Galler, R. (2015), "Numerical calibration of a yield limit function for rock materials by means of the Brazilian test and the uniaxial compression test", *J. Rock. Mech. Min. Sci.*, **74**, 24-29.

Nian, T., Wang, G. and Song, H. (2017), Open tensile fractures at depth in anticlines: A case study in the Tarim basin, NW china", *Terra Nova*, **29**(3), 183-190.

Saksala, T., Hokka, M., Kuokkala, V.T. and Mäkinen, J. (2013), "Numerical modeling and experimentation of dynamic Brazilian disc test on Kuru granite", *J. Rock. Mech. Min. Sci.*, **59**, 128-138.

Seto, M., Nag, D. and Vutukuri, V. (1999), "In-situ rock stress measurement from rock cores using the acoustic emission method and deformation rate analysis", *Geotech. Geol. Eng.*, **17**(3-4), 241-266.

Seto, M., Utagawa, M., Katsuyama, K., Nag, D. and Vutukuri, V. (1997), "In situ stress determination by acoustic emission technique", *J. Rock. Mech. Min. Sci.*, **34**(3-4), 281.

Tuncay, E. and Ulusay, R. (2008), "Relation between Kaiser effect levels and pre-stresses applied in the laboratory", *J. Rock. Mech. Min. Sci.*, **45**(4), 524-537.

Villaescusa, E., Seto, M. and Baird, G. (2002), "Stress measurements from oriented core", *J. Rock. Mech. Min. Sci.*, **39**(5), 603-615.

Wu, B., Chen, R. and Xia, K. (2015), "Dynamic tensile failure of rocks under static pre-tension", *J. Rock. Mech. Min. Sci.*, **80**, 12-18.

Xue, L., Qin, S., Sun, Q., Wang, Y., Lee, L.M. and Li, W. (2014), "A study on crack damage stress thresholds of different rock types based on uniaxial compression tests", *Rock Mech. Rock Eng.*, **47**(4), 1183-1195.

Yang, S.Q., Ranjith, P. and Gui, Y.L. (2015), "Experimental study of mechanical behavior and x-ray micro ct observations of sandstone under conventional triaxial compression", *Geotech. Test. J.*, **38**(2), 179-197.

Yuan, R. and Shen, B. (2017), "Numerical modelling of the contact condition of a Brazilian disk test and its influence on the tensile strength of rock", *J. Rock. Mech. Min. Sci.*, **93**, 54-65.

CC