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Different Approaches to Study the Kaiser Effect in Rocks in Triaxial Loading

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Summary From a literature review, it can be accepted that the Kaiser effect does exist in rocks or rock-like materials in uniaxial loading. Regarding the effect of water, load level and retention time of the Kaiser effect recovery, different opinions exist. For a rock specimen in triaxial loading, similar to the in-situ stress state, conflicting results have been reported in the literature. To clarify this issue, different approaches have been undertaken in the present investigations.

This paper will introduce different approaches to investigate the Kaiser effect in two natural rocks, namely, granite and sandstone, and one artificial rock-like material under triaxial loading. One conclusion is that the confining pressure does affect the Kaiser effect and that the stress determined in axial direction from the Kaiser effect point decreased as the confining pressure increased.

The paper also reports the findings on the retention time of the Kaiser effect.

1. INTRODUCTION

It has been sought to measure in-situ rock stresses by an easy, fast, economical and reliable method. The discovery of the Kaiser effect in metals (Kaiser, 1953), which suggested that previous stress might be detected by stressing the metal to the point where there was a substantial change in acoustic emission rate, brought a promising way to measure stresses.

The Kaiser effect point is interpreted, by definition, to be the stress level at which there is a rapid increase in the slope of AE accumulative count curve shown in Figure 1. Arrow shows the Kaiser effect point.

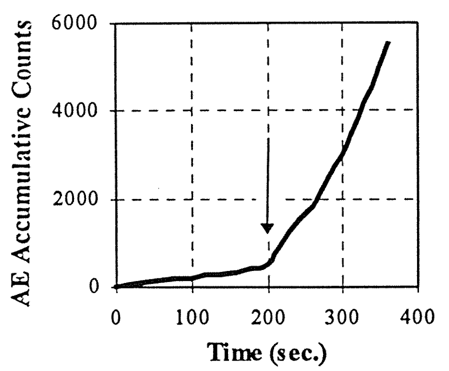

Figure 1. Illustration of the Kaiser effect.

In 1963, Goodman confirmed that the Kaiser effect exists in three rocks in his experiments. In 1976, Kanagawa, Hayashi and Kitahara reported the Kaiser effect method to determine rock stress state. The results from the Kaiser effect method were basically consistent with those measured by the overcoring method. Since then, a lot of research work has been undertaken to investigate the Kaiser effect in different rocks, under different loading levels. The effects of confining pressure, environment i.e. water and temperature, the retention time of the Kaiser effect and specimen preparation technique on the Kaiser effect have also been studied.

Up to now, it is widely accepted that the Kaiser effect does exist in rocks or rock-like materials in uniaxial loading. Different opinions exist on the role of various factors mentioned above on the Kaiser effect.

Kurita and Fujii (1979) reported that the total counts of AE decreased considerably under wet conditions, and the take-off point expected from the Kaiser effect could not be identified. Yoshikawa and Mogi (1981) reported no remarkable influence of water and temperature on the Kaiser effect of the AE activity.

Goodman (1963) reported that 40-60% of AE was recovered in a few hours in two types of sandstones and a quartz. That means that the Kaiser effect could only remain in rock for a very short time. However, Yoshikawa and Mogi (1981) reported that the recovery of the Kaiser effect was observed from several hours to 7 days. Kurita and Fujii (1979) observed the Kaiser effect existence up to 1 month.

Seto et al. (1992) observed the Kaiser effect existence up to 400 days. Hardy and Shen (1992) observed the Kaiser effect existence up to 36 months.

As for a rock specimen in triaxial loading, similar to the in-situ stress state, conflicting results have been reported. Holcomb (1983) conducted experiments on Westerly granite specimens with diameter 38 mm and height 95 mm. He used the same specimen under cyclic loading, the first loading to set up stress history, the second loading to determine the previous stress. After two cycles, he increased the confining pressure to a higher value, then repeated the same procedure. In this way, he observed that as the confining pressure increased, the stress required for the Kaiser effect also increased. Hughson and Crawford (1987) obtained a relationship between the recalled axial stress and deviatoric pre-stress after conducting tests on sandstone specimens of 13 mm diameter subcored from a larger core which was loaded under different combinations of axial and confining stresses.

On the other hand, several authors reported no effect of confining pressure on the Kaiser effect (Kanagawa et al., 1976; Niiseki et al., 1986; Michihiro et al. 1991/92; Momayez and Hassani, 1992; Seto et al., 1996).

In order to clarify the confining pressure influence on the determination of the Kaiser effect, different approaches have been undertaken in the present investigations.

2. EXPERIMENTS IN LABORATORY

2.1 Rock Specimens

The rocks selected for investigations are sandstone from Gosford quarry and West Australian granite. Another one is a rock-like material, made with sand and plaster (Vutukuri and Moomivand, 1996). The specimens were cored out directly from 300 mm blocks. The diameter is 45 mm and the average height is 100 mm. All the cores were prepared in accordance with ISRM (1981) standards.

2.2 Test Equipment

All the specimens were loaded uniaxially and triaxially by a servo-controlled testing machine, Schenck Trebel, with displacement control.

The MISTRAS 2001 AE detection and analysis computer system was employed with two piezoelectric transducers and two preamplifiers. AE signals and axial stresses were transferred into the computer system. The gain of preamplifier was set at 40 dB. The gain inside the computer system was set at 20 dB. The threshold was set to 45 dB. The frequency filter was set at 20-200 kHz for channel one and 200-1200 kHz for channel two.

2.3 Data Processing

There are two methods to process the data. The first is to use the functions provided in the software, Mistras 2001. In this software, AE data can be saved through the following parameters: Time, Hits, Cycles, Duration, Counts, Energy, Amplitude, Risetime, Channel, Average Frequency (kHz), Threshold. Stress as well as strain are also recorded. These parameters could be presented as a graph in the form of hit, count, energy, amplitude and stress versus time, or versus each other. The advantage of this method is that one can easily process the data in graphic form without any loss of the data. The disadvantage is that it can not be presented as an equation. It is common to plot time or load readings versus the AE hit, count, and energy. The slope change point in these graphs is used to estimate the previous stress. This method was used by many researchers, such as Kanagawa et al. (1976), Yoshikawa and Mogi (1981), Seto et al. (1992, 1996).

The other method is to change the original data from binary form into text form to be used by other software, such as Datafit, Excel. The advantage is the data can be represented not only as a graph but also as an equation by using other software. The disadvantage is that it can easily introduce error, depending on personal experience, because the data is so voluminous that one might only select some of it. The maximum curvature method proposed by Momayez et al. (1992) and the pivot point method suggested by Hardy and Shen (1992) belong to this category.

Generally, the Kaiser effect point is identified by observing substantial AE increase or the slope change if high resolution data is available. Otherwise, the maximum curvature method (Momayez et al., 1992) is employed.

2.4 Approach One

In this approach, there are two steps: loading and unloading, and reloading.

The first step is loading and unloading. In this step, a designed triaxial stress history of a rock specimen, which is similar to that of the in-situ stress state is created. The cylindrical rock specimen is loaded in a triaxial cell to the designated values. The vertical pressure (σ_1) is applied by the Schenck machine at the loading rate of 100 μm/min. The confining pressure (σ_3) is applied manually to a pre-set value at the same loading rate as used for axial pressure application. Then the vertical pressure is increased to a pre-set value. After maintaining the loading for 40 minutes, the specimen is unloaded while maintaining the designated difference between axial and confining pressures until the confining pressure becomes zero first, and then the vertical pressure decreases to zero.

The second step is reloading. In this step, the rock specimen is still in the triaxial cell, untouched in order to prevent any AE noises arising from any mismatch between the specimen and plates. The specimen is loaded uniaxially in the vertical direction until the pressure is 5 to 10 MPa over the pressure difference between the pre-set vertical pressure and the confining pressure at the rate of 100 μm/min.

This approach is different from that used by others; the specimen is not removed from the cell and reloaded immediately after unloading. The obvious advantage is that the AE noises are greatly reduced and the Kaiser effect is clearly seen. It is an effective approach to investigate the effect of the confining pressure on the determination of the Kaiser effect. But it should be pointed out that it is not realistic to measure in-situ stress in this way.

2.5 Approach Two

This approach was reported by Seto et al. (1996). In this approach, after preparing the specimen in a triaxial cell with a pre-set loading history, the specimen is removed from the triaxial cell and loaded uniaxially to evaluate the pre-set stress. The pre-loading was done twice, each of 40 minutes duration. The re-loading for the determination of the Kaiser effect was also done twice; the first at a loading rate of 50 μm/min and the second at a loading rate of 100 μm/min. The difference in this approach from that of others is that the specimen is reloaded twice to determine the Kaiser effect.

2.6 Experimental Results

In approach one, the experiments are on granite, sandstone and one artificial rock-like material. Figure 2 shows the results of AE accumulative counts versus time, and the corresponding vertical stress versus time for granite. From this graph, the Kaiser effect take-off point (shown by arrow) could be clearly estimated at 20 MPa, which is equal to the difference between the vertical stress 50 MPa and the confining stress 30 MPa, applied in pre-loading. Similarly, Figure 3 shows the Kaiser effect point as 10 MPa for sandstone. The applied stresses were the vertical stress 15 MPa and the confining stress 5 MPa. Figure 4 shows that the estimated stress is 9 MPa for the artificial sample; this specimen had a vertical stress of 18 MPa and the confining stress of 10 MPa.

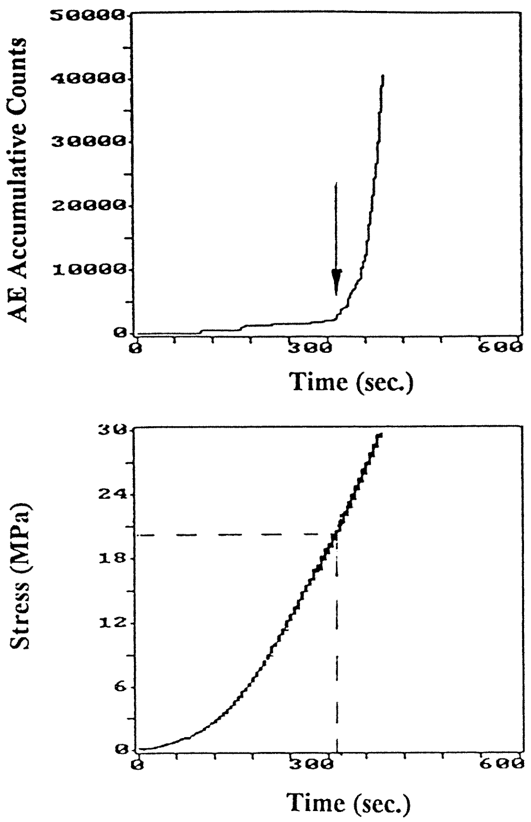

Figure 2. Accumulative counts and stress versus time for granite.

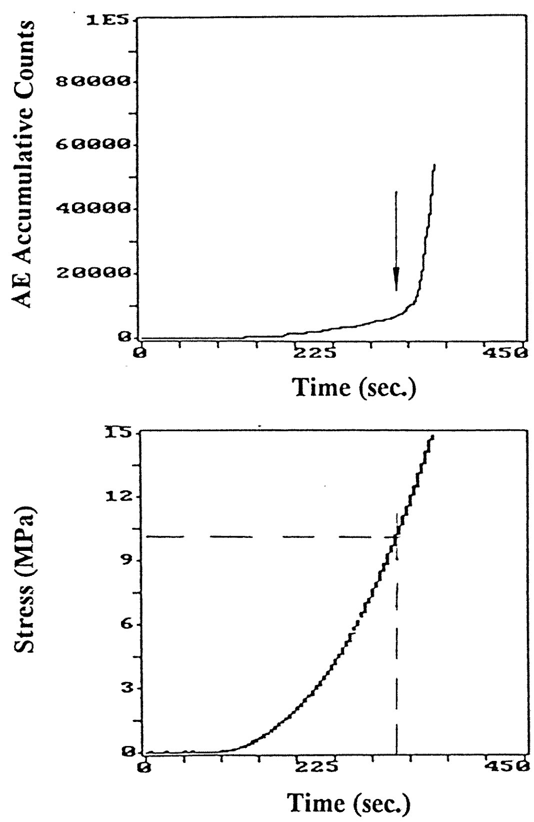

Figure 3. Accumulative counts and stress versus time for sandstone.

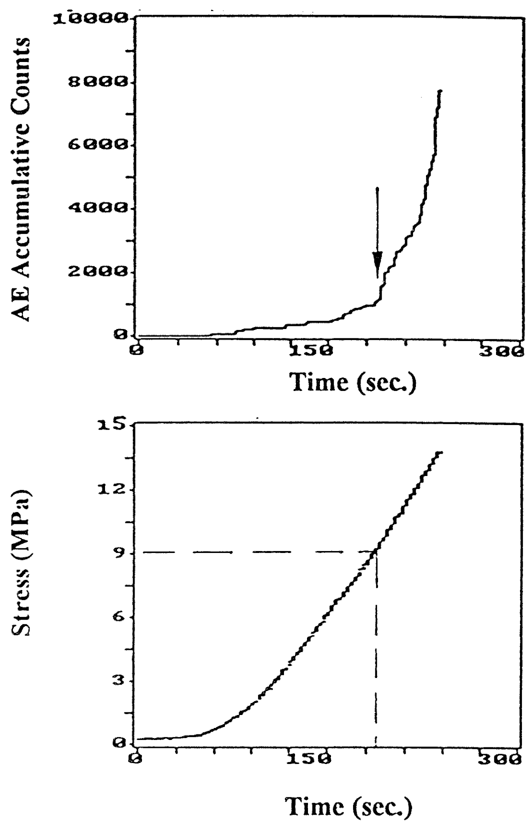

Figure 4. Accumulative counts and stress versus time for artificial rock-like material.

A series of experiments was carried out in order to investigate the effect of confining stress on the Kaiser effect point for determining axial stress. The results from the experiments by approach one are given in Table 1.

Table 1. Estimated stress by approach one.

Rock types	Pre-load stress (MPa)			Estimated stress by Kaiser effect (MPa)
	axial σ_1	confin-ing σ_3	differential σ_1-σ_3	
Granite	50	10	40	30
Granite	50	20	30	28
Granite	50	30	20	20
Granite	40	20	20	14
Sandstone	20	0	20	20
Sandstone	20	10	10	10
Sandstone	24	15	9	9
Sandstone	15	5	10	10
Sandstone	15	10	5	6
Artificial	15	5	10	10
Artificial	15	10	5	5.5
Artificial	18	10	8	9

The results indicate that the stress determined in axial direction from the Kaiser effect point decreased as the confining pressure increased, as shown in Figure 5. However, this stress is more or less equal to the differential stress (i.e. axial stress - confining stress).

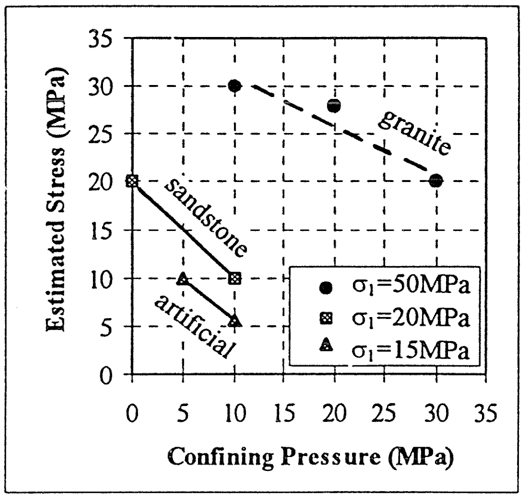

Figure 5. The relationship between estimated stress and confining pressure in approach one.

In approach two, the experiments are on granite and sandstone specimens. The results are listed in Tables 2 and 3 for granite and sandstone respectively. Zero in Tables represents that the Kaiser effect point can not be identified. A/N represents no second loading. The results indicate that the stress determined in axial direction from the Kaiser effect point generally decreased as the confining pressure increased, as shown in Figures 6 and 7 for granite and sandstone respectively.

Table 2. Estimated stress by approach two on granite.

Speci-men No.	Pre-load stress (MPa) σ_1, σ_3	Duration	Estimated stress by Kaiser effect (MPa)	
			1st load	2nd load
gtks08	50, 10	10 days	0	36
gtks06	50, 25	10 min	22	21
gtks04	50, 30	14 days	0	28
gtks10	50, 40	14 days	11	13
gtks40	50, 30	30 days	0	0
gtks301	40, 15	10 min.	26	A/N
gtks50	40, 20	3 days	22	20
gtks90	40, 25	3 days	13	12
gtks02	40, 20	14 days	0	18
gtks20	40, 20	30 days	0	0
gtks11	30, 20	3 days	8	6.5

Table 3. Estimated stress by approach two on sandstone.

Specimen No.	Pre-load stress (MPa) σ_1, σ_3	Duration	Estimated stress by Kaiser effect (MPa) 1st load	2nd load
stks19	25, 10	10 days	8	11
stks21	25, 15	8 days	8.5	6.5
stks23	25, 5	20 days	15	20
stks20	24, 15	8 days	7	6
stks16	20, 10	10 min.	0	11.5
stks22	20, 10	7 days	13.5	12
stks15	15, 5	7 days	9	10
stks25	15, 5	21 days	0	0
stks18	25, 10	30 days	0	0
stks81	30, 10	20 days	24	A/N

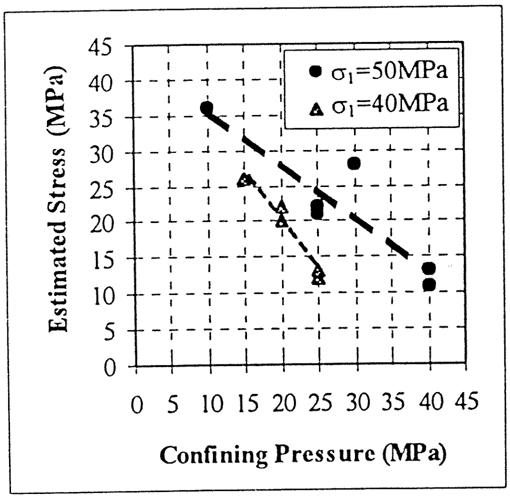

Figure 6. The relationship between estimated stress and confining pressure for granite in approach two.

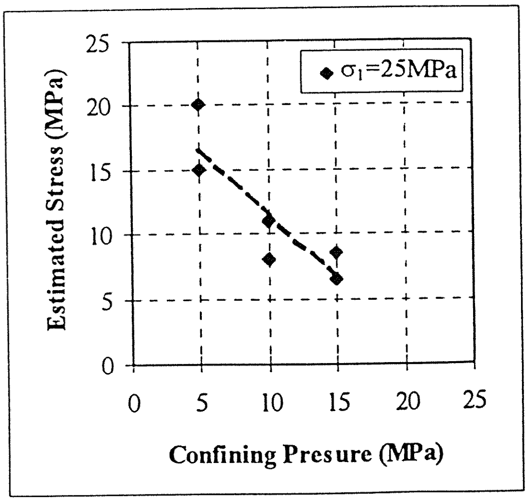

Figure 7. The relationship between estimated stress and confining pressure for sandstone in approach two.

2.7 Discussion

In two different approaches, the Kaiser effect point could be more clearly determined in approach one than that in approach two. One reason for this is the greatly reduced noises in this approach.

In approach 2, the Kaiser effect point can not be identified in the first loading in some cases. But it can be determined in the second loading if the duration between the pre-load and load is within 3 weeks. For instance, the Kaiser effect point could not be identified in the first loading for a granite specimen (gtks02) after two weeks. Even in the second loading the Kaiser effect point is still hardly identified by directly observing the slope change in the graph of AE accumulative counts versus time, as shown in Figure 8. The maximum curvature method was used in this case. The principle of this method is to find out the point where there is the maximum curvature. According to this method, the graph in Figure 8 can be expressed by the following function as shown in Figure 9:

$$f(t) = 1356.2e^{0.413*1.011^t} \qquad (1)$$

where f(t) is the function of AE accumulative counts and t is time.

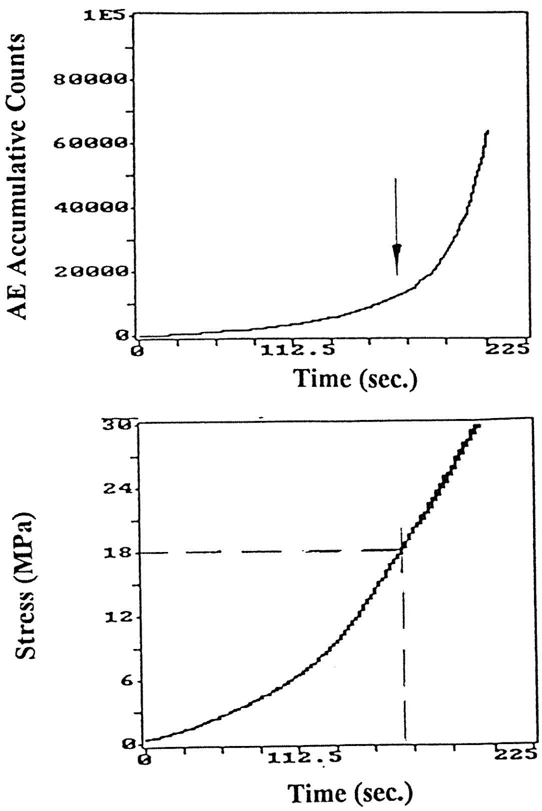

Figure 8. Accumulative counts and stress versus time for granite in the second loading.

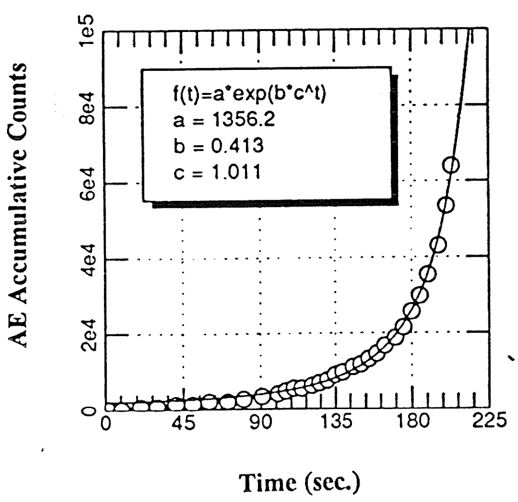

Figure 9. Illustration of curve-fitting.

Then the angle (θ) between this curve and the horizontal axis (time) can be calculated and it is differentiated to obtain the curvature K.

$$\theta = \arctan(f(t) / t) \tag{2}$$

$$K = d\theta / dt \tag{3}$$

By plotting K versus time, the maximum curvature is determined at the time of 153 seconds as shown in Figure 10.

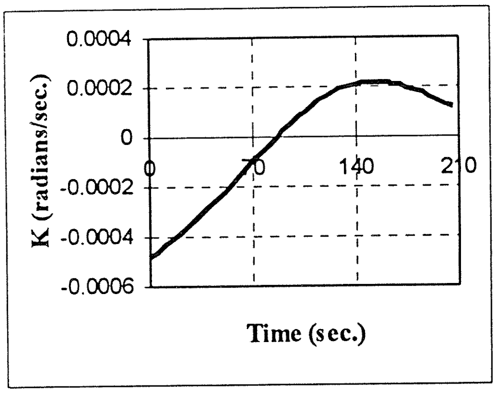

Figure 10. Curvature variation with time.

At 153 seconds, the stress is 18 MPa.

The time between pre-load and load of the test specimen has an effect on the Kaiser effect and it is recommended to evaluate the stress by the Kaiser effect within 2 to 3 weeks.

3. CONCLUSIONS

Approach one has been proposed to investigate the influence of the confining pressure on the determination of the Kaiser effect. It can be used to identify the Kaiser effect in triaxial loading condition clearly and effectively. Two types of rock and one rock-like material have been employed in the experiments. The results show that the stress evaluated in axial direction from the Kaiser effect point decreased as the confining pressure increased. This conclusion is generally consistent with the results from approach two. The Kaiser effect could be determined on sandstone and granite specimens within 2~3 weeks after pre-loading.

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