CHAPTER VI
ANALYSIS OF RESULTS

6.1 Introduction

The objective of this chapter is to determine the relationship between CAI and joint characteristics. The effects of joint numbers and joint apertures on CAI are quantitatively derived. This allows predicting the CAI values as affected by the joint variables occurring beyond those used in this study. The work and CERCHAR specific energy exerting on the jointed rocks are also derived to compare with those of the intact ones that have been widely performed elsewhere.

6.2 Correlation between CAI and joint apertures

Figure 6.1 plots CAI as a function of joint aperture (e) for all tested rock specimens. Each data point in the diagram represents the average CAI values obtained from five stylus pins. For all rock types CAI's decrease linearly with increasing joint apertures. This holds ture for all joint numbers. The decrease of CAI can be represented by:

$$\mathrm{CAI}=\alpha \cdot e+\beta \tag{6.1}$$

where α and β are empirical constants. Their numerical values are given in Table 6.1. Good correlations are obtained (R2 > 0.9). The parameter α represents the negative slope of the linear relation. Each rock type tends to show similar values of α for different joint numbers. Strong rock (basalt) shows higher values of α than the softer ones (limestone and sandstone). This implies that the effects of joint apertures are more pronounced in the strong rocks than in the softer ones. The parameter β represents the intercept of the linear curves. The fewer joint numbers yield the higher β values where intact rocks show the highest value as shown by solid data point for compassion. In addition, strong rock (basalt) gives higher β values than the softer ones (limestone and sandstone).

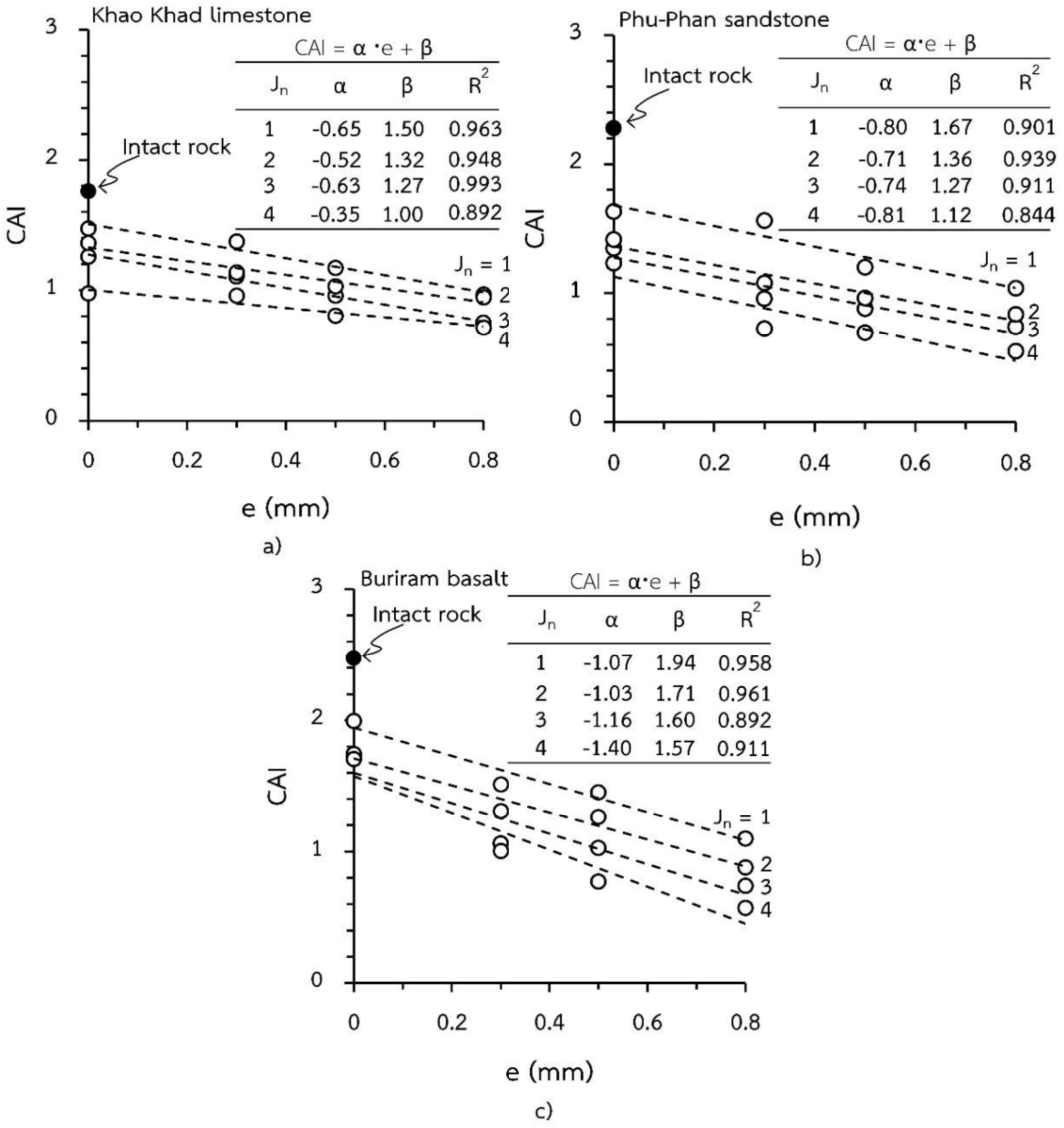

Figure 6.1 CAI as a function of joint aperture (e) for different numbers of joints (J_n) for Khao Khad limestone (a), Phu Phan sandstone (b) and Buriram basalt (c).

Table 6.1 CAI and joint apertures for all rock types.

Number of joints (J_n)	Aperture (e) (mm)	CAI = $\alpha \cdot e + \beta$								
		Rock type								
		Khao Khad limestone			Phu Phan sandstone			Buriram basalt		
		α	β	R^2	α	β	R^2	α	β	R^2
0 (Intact rock)	-	-	-	-	-	-	-	-	-	-
1	0 0.3 0.5 0.8	-0.65	1.51	0.963	-0.80	1.67	0.901	-1.07	1.94	0.958
2	0 0.3 0.5 0.8	-0.52	1.32	0.948	-0.71	1.36	0.939	-1.03	1.71	0.961
3	0 0.3 0.5 0.8	-0.63	1.27	0.993	-0.73	1.27	0.911	-1.16	1.60	0.892
4	0 0.3 0.5 0.8	-0.35	1.00	0.892	-0.81	1.12	0.844	-1.40	1.57	0.911

6.3 Correlation between CAI and joint numbers

CAI's are presented as a function of joint numbers (J_n) in Figure 6.2 They decrease linearly as J_n increases. No significant trend of the decreasing rates has been observed. This is probably due to intrinsic variability of the rocks. Strong rock (basalt) nevertheless tends to show higher curve than the softer ones (sandstone and limestone). The CAI for intact rock is shown as a solid point in the diagram (at J_n = 0) for comparison. The linear curve can be represented by:

$$CAI = \chi \cdot J_n + \gamma \tag{6.2}$$

where χ and γ are empirical constants, with their numerical values provided in Table 6.2. A good correlation is observed ($R^2 > 0.9$), except for strong rock (basalt of aperture 0 mm), which has the lowest correlation with $R^2 > 0.7$.

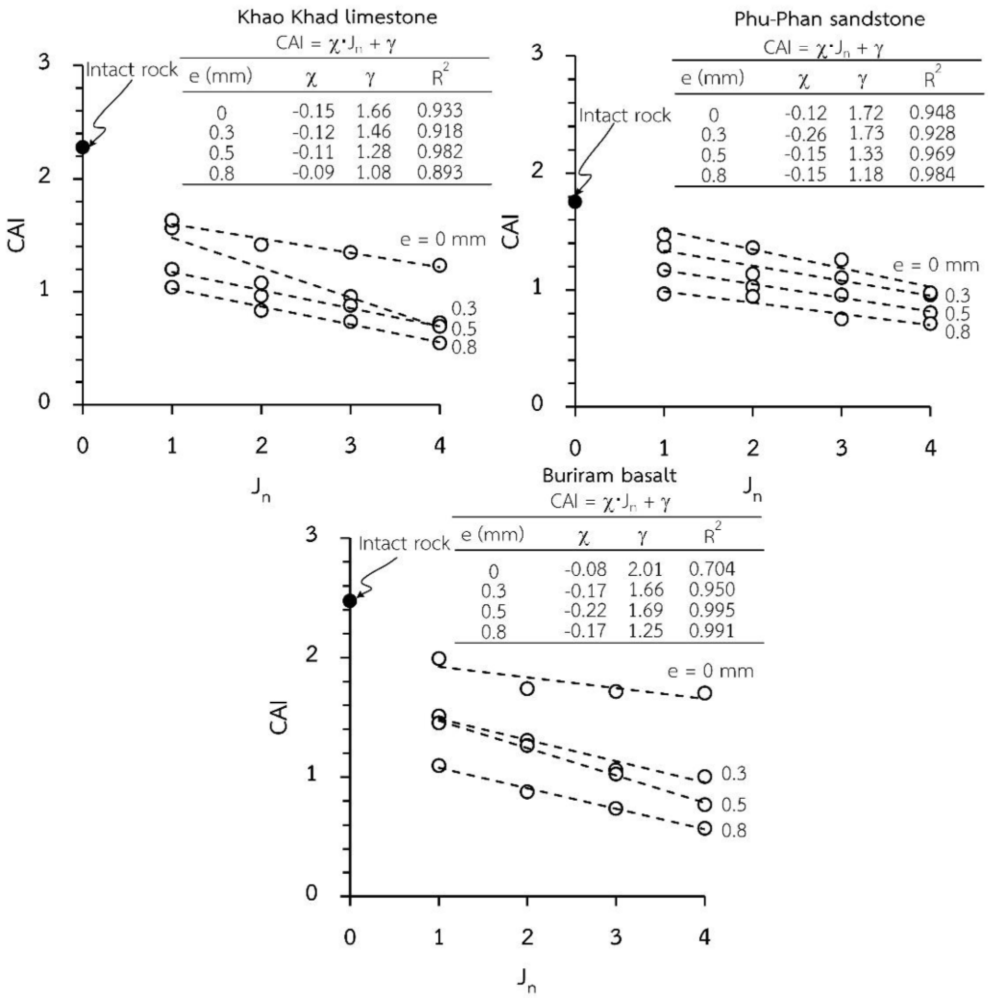

Figure 6.2 CAI as a function of joint numbers (J_n) for different apertures (e) for Khao Khad limestone (a), Phu Phan sandstone (b) and Buriram basalt (c).

Table 6.2 CAI and joint numbers for all rock types.

Number of joints (J_n)	Aperture (e) (mm)	CAI = $\chi \cdot J_n + \gamma$								
		Rock type								
		Khao Khad limestone			Phu Phan sandstone			Buriram basalt		
		χ	γ	R^2	χ	γ	R^2	χ	γ	R^2
0 (Intact rock)	-	-	-	-	-	-	-	-	-	-
1	0 0.3 0.5 0.8	-0.15	1.66	0.933	-0.12	1.72	0.948	-0.08	2.01	0.704
2	0 0.3 0.5 0.8	-0.12	1.46	0.918	-0.26	1.73	0.928	-0.17	1.66	0.950
3	0 0.3 0.5 0.8	-0.11	1.28	0.982	-0.15	1.33	0.969	-0.22	1.69	0.995
4	0 0.3 0.5 0.8	-0.09	1.08	0.893	-0.15	1.18	0.984	-0.17	1.25	0.991

6.4 Lateral force and scratching distance

An exponential equation is proposed to represent the lateral force (F) as a function of scratching distance (d_s). The primary objective is to calculate the specific energy of the stylus pin along the scratching distance. Similar form of the equation has been used by Kathancharoen and Fuenkajorn, (2023) for ten types of intact rocks.

$$F = a \cdot [1 - \exp \cdot (-b \cdot d_s)] \qquad (6.3)$$

where a and b are empirical constants. Their numerical values are given in Table 6.3. Good correlations are obtained ($R^2 > 0.7$).

Table 6.3 Empirical constants (a and b) in equation (6.3).

Number of joint (J_n)	Aperture (e) (mm)	$F = a \cdot [1 - \exp \cdot (-b \cdot d_s)]$								
		Rock type								
		Khao Khad limestone			Phu Phan sandstone			Buriram basalt		
		a	b	R^2	a	b	R^2	a	b	R^2
0 (Intact rock)	-	1.40	-1.19	0.967	1.54	-1.05	0.961	2.06	-0.42	0.895
1	0	1.78	-0.56	0.867	1.51	-1.34	0.911	2.14	-0.85	0.861
	0.3	3.21	-0.32	0.907	1.86	-0.63	0.856	3.11	-2.87	0.944
	0.5	3.81	-0.28	0.893	2.16	-0.44	0.875	4.58	-10.75	0.872
	0.8	4.64	-0.20	0.824	2.58	-0.61	0.946	5.76	-13.78	0.826
2	0	2.11	-0.27	0.834	2.43	-0.64	0.897	1.89	-2.49	0.794
	0.3	5.56	-0.11	0.818	3.96	-0.17	0.900	4.12	-11.02	0.844
	0.5	14.0	-0.04	0.891	4.53	-0.16	0.894	6.57	-29.16	0.765
	0.8	12.5	-0.05	0.859	4.72	-0.17	0.906	9.24	-38.15	0.842
3	0	2.13	-0.39	0.712	2.66	-0.70	0.901	4.12	-3.89	0.764
	0.3	4.80	-0.17	0.867	10.26	-0.07	0.830	5.21	-14.87	0.773
	0.5	5.20	-0.16	0.849	10.86	-0.07	0.896	6.88	-34.60	0.822
	0.8	4.45	-0.28	0.846	12.81	-0.06	0.829	6.44	-47.72	0.792
4	0	2.86	-0.23	0.799	2.78	-0.75	0.956	3.57	-13.85	0.793
	0.3	4.22	-0.22	0.860	11.11	-0.03	0.923	6.30	-18.37	0.866
	0.5	5.37	-0.16	0.880	19.266	-0.04	0.888	7.26	-42.57	0.922
	0.8	7.96	-0.10	0.895	186.45	-0.09	0.930	8.22	-51.21	0.919

Figures 6.3 through 6.5 plot the lateral force as a function of scratching distance. The intact rocks shown the lowest force for all rock types. The larger joint numbers and apertures require the higher lateral force along the scratching length. The forces reach maximum at the end of the scratching length. Joint frequency (J_n) tends to have stronger effect on rock abrasiveness than the joint aperture (e).

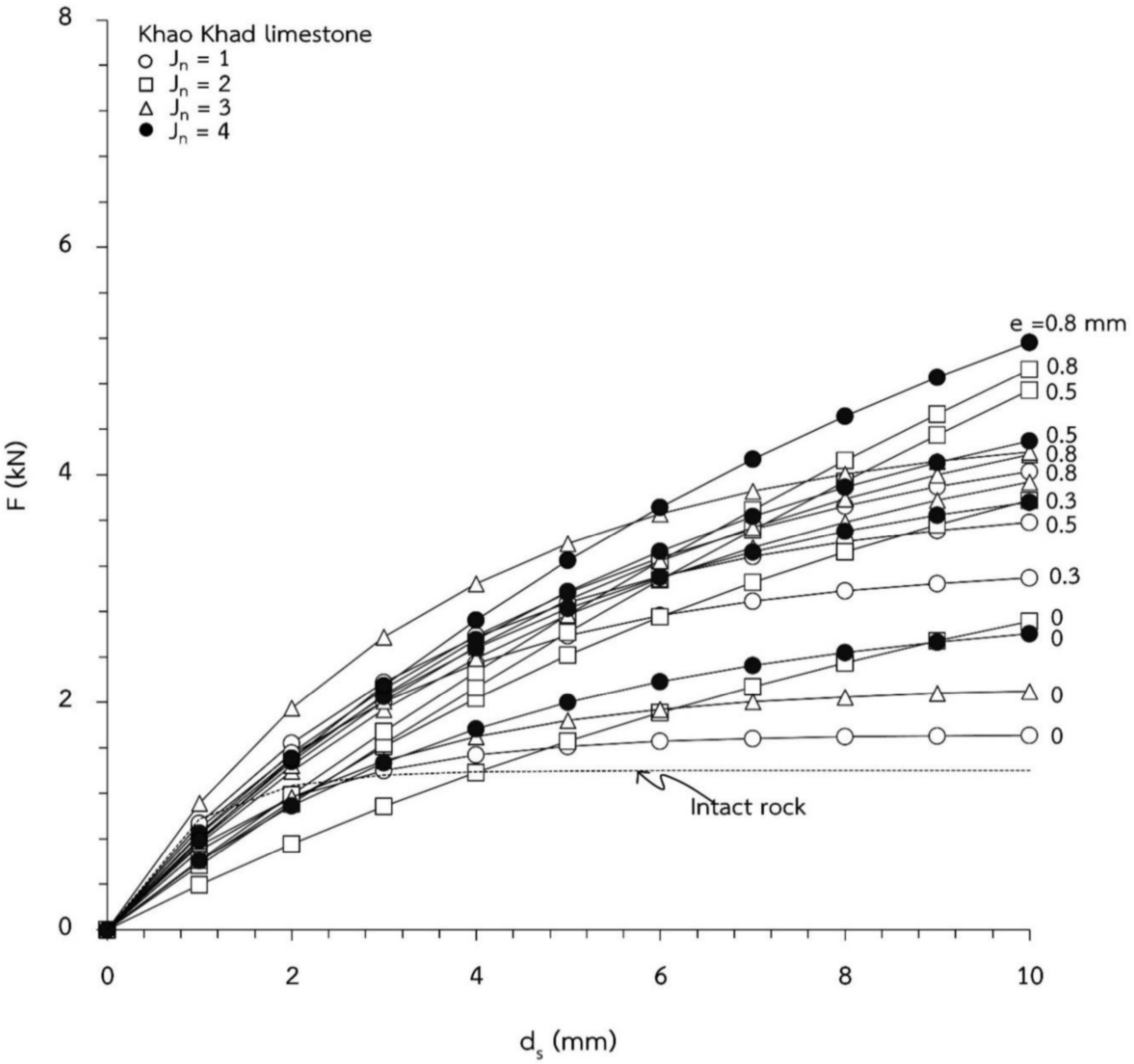

Figure 6.3 Lateral force as a function of scratching distance (d_s) of for different joint numbers and apertures for Khao Khad limestone.

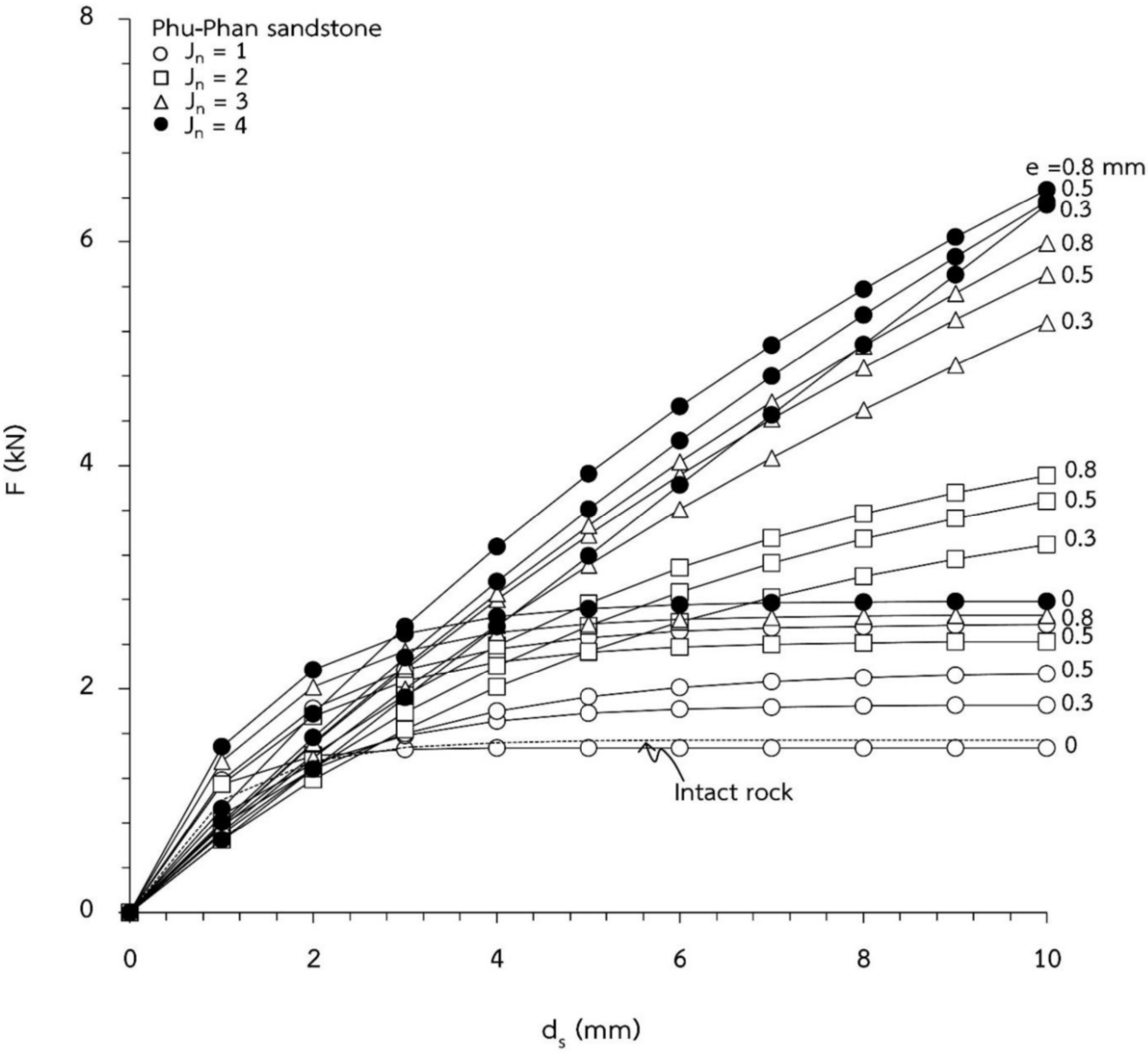

Figure 6.4 Lateral force as a function of scratching distance (d_s) of for different joint numbers and apertures for Phu Phan sandstone.

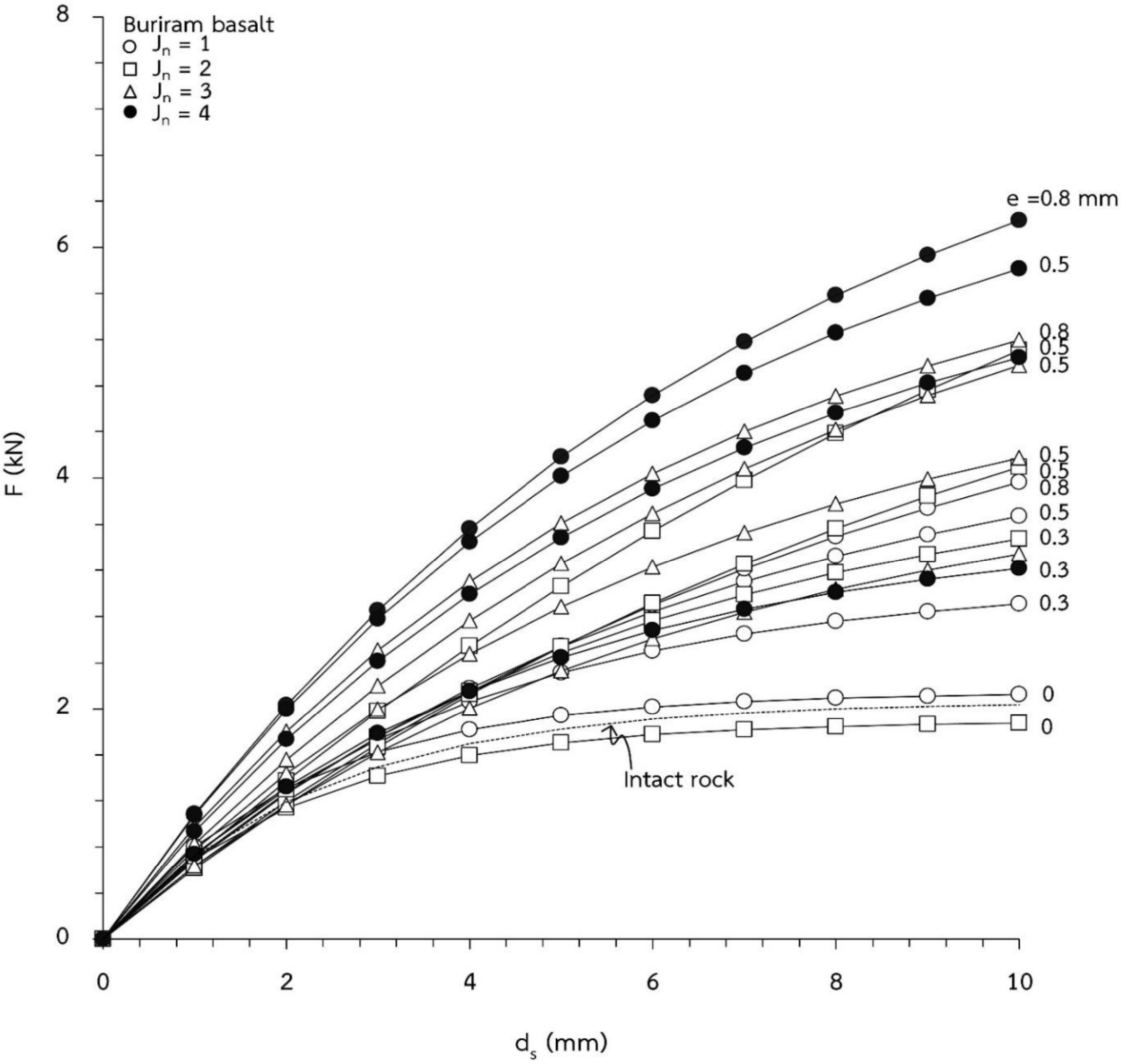

Figure 6.5 Lateral force as a function of scratching distance (d_s) of for different joint numbers and apertures for Buriram basalt.

6.5 Correlation between scratching groove volume (v) and joint number (J_n) and aperture (e)

The groove volume is affected by both joint number (J_n) and aperture (e). The number of joints increases the groove volume. This relationship can be expressed by the liner equation:

$$V = \omega J_n + \tau \quad (6.4)$$

where ω and τ are empirical constants, with their numerical values provided in Table 6.4.

Table 6.4 Empirical constants (ω and τ) in equation (6.4).

Number of joint (J_n)	Aperture (e) (mm)	$V = \omega \cdot J_n + \tau$								
		Rock type								
		Khao Khad limestone			Phu Phan sandstone			Buriram basalt		
		ω	τ	R^2	ω	τ	R^2	ω	τ	R^2
0 (Intact rock)	-	-	-		-	-		-	-	
1	0 0.3 0.5 0.8	2.76	-2.81	0.820	5.37	-2.10	0.956	3.40	-2.68	0.667
2	0 0.3 0.5 0.8	2.19	2.86	0.620	7.46	1.50	0.893	4.11	0.73	0.850
3	0 0.3 0.5 0.8	6.58	6.42	0.976	12.79	6.45	0.873	12.64	-0.20	0.964
4	0 0.3 0.5 0.8	9.48	9.67	0.933	14.63	11.91	0.925	15.25	2.13	0.961

The scratching groove volume however decreases as the joint aperture increases. This holds true for all tested rock shown in Figures 6.6. Note that the groove volume considered here is only from the scratching of the intact portion of the rock between the joints, excluding the joint apertures.

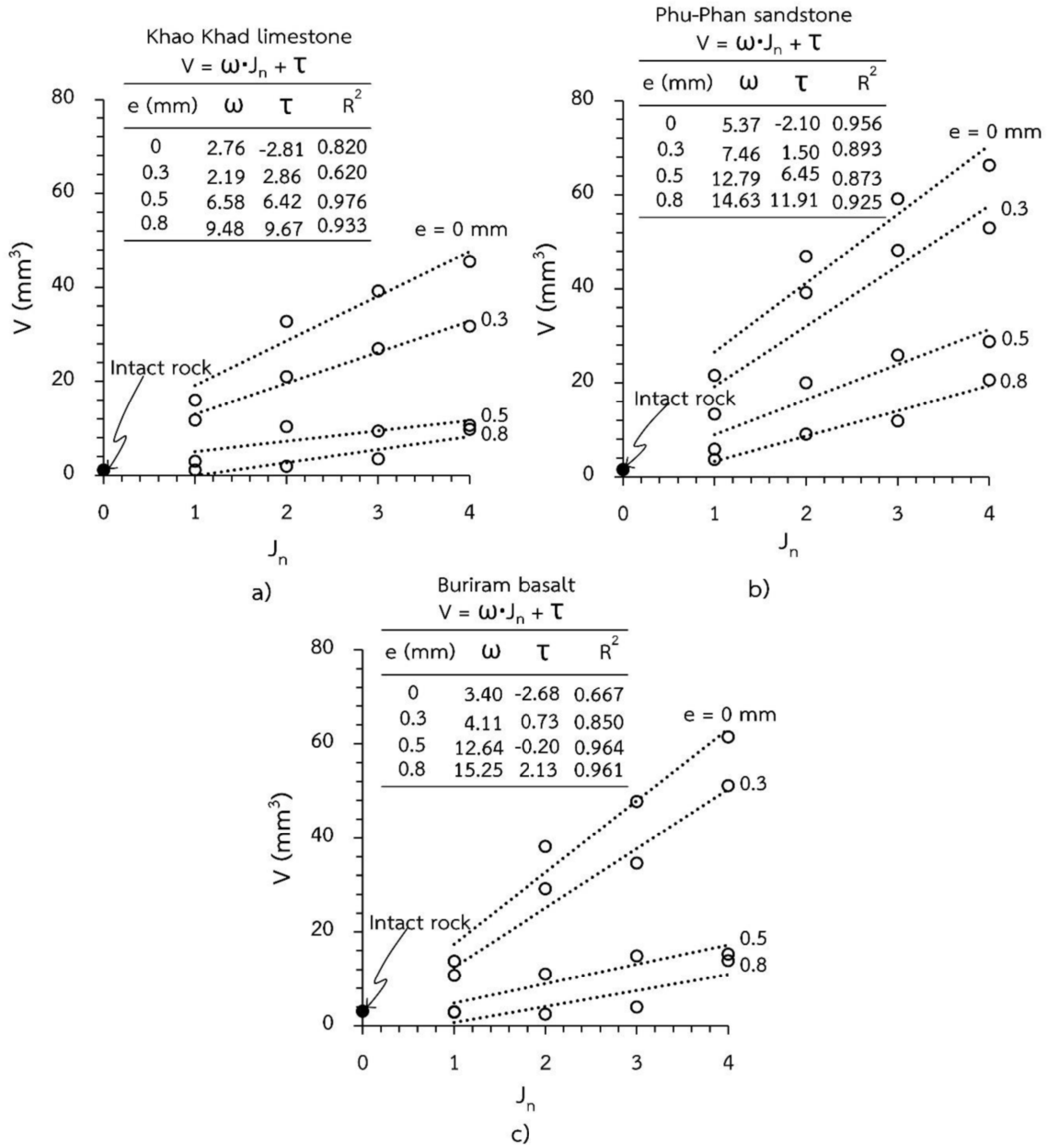

Figure 6.6 Groove volume as a function of joint numbers (J_n) for different apertures (e) for Khao Khad limestone (a), Phu Phan sandstone (b) and Buriram basalt (c).

6.6 Work and energy

Analysis in this study involves calculating the specific energy required for scratching, known as the CERCHAR specific energy (CSE), as proposed by Hamzaban, Memarian, and Rostami, (2018).

CSE is calculated by comparing the work (energy) used for scratching with the volume of the groove created on the intact rock surface excluding the joints. The fundamental equation for calculating the work is as follows (Zhang, Konietzky, and Frühwirt, 2020).:

$$W = \int_{d_s=0}^{10} F \cdot d_S \tag{6.5}$$

The work (W) is calculated based on the lateral force as a function of scratching displacement (F-ds) over a scratching distance of 10 millimeters. The specific energy can be calculated using the following equation (Zhang, Konietzky et al., 2020).

$$CSE = \frac{W}{V} = \frac{\int_{d_s=0}^{10} F \cdot d_s}{V} \tag{6.6}$$

The results of calculation are given in Table 6.5. CSE values as a function of joint CAI are plotted as a function of CAI in Figures 6.7 through 6.9.

The energy required to scratching the jointed rock per unit groove volume increases exponentially with CAI, where the greater joint numbers (J_n) use the lower scratching energy. Basalt (strong rock) shows higher CSE and CAI values than sandstone and limestone (softer rocks). For all tested rocks, wider joint apertures require lower specific energy to scratch.

Table 6.5 Results of work and energy for all rock types and joint characteristics.

Number of joints (J_n)	Aperture (e) (mm)	Rock type					
		Khao Khad limestone		Phu Phan sandstone		Buriram basalt	
		W (J)	CSE (J/mm^{-1})	W (J)	CSE (J/mm^{-1})	W (J)	CSE (J/mm^{-1})
0 (Intact rock)	-	11.76	10.29	12.93	8.13	40.85	13.23
1	0	11.39	10.12	25.81	6.99	34.42	11.49
	0.3	26.24	8.70	30.32	5.14	25.12	8.72
	0.5	94.79	8.04	51.83	4.00	61.16	5.68
	0.8	79.63	4.9	86.48	3.88	70.52	5.11
2	0	15.92	8.26	40.62	5.06	22.37	8.95
	0.3	56.98	5.50	101.51	4.46	70.35	6.38
	0.5	109.92	5.22	139.98	3.56	92.81	3.20
	0.8	122.028	3.72	165.61	3.52	122.11	3.18
3	0	16.81	4.79	33.84	3.78	17.87	4.48
	0.3	37.50	4.51	98.33	3.51	47.14	3.16
	0.5	39.10	1.45	127.87	2.84	69.11	1.99
	0.8	42.43	0.95	207.85	2.65	59.44	1.24
4	0	31.75	3.33	23.75	2.78	29.33	2.11
	0.3	32.53	3.23	80.29	2.14	30.72	2.00
	0.5	35.20	1.02	113.57	2.13	68.24	1.33
	0.8	35.58	0.77	141.75	1.14	57.79	0.94

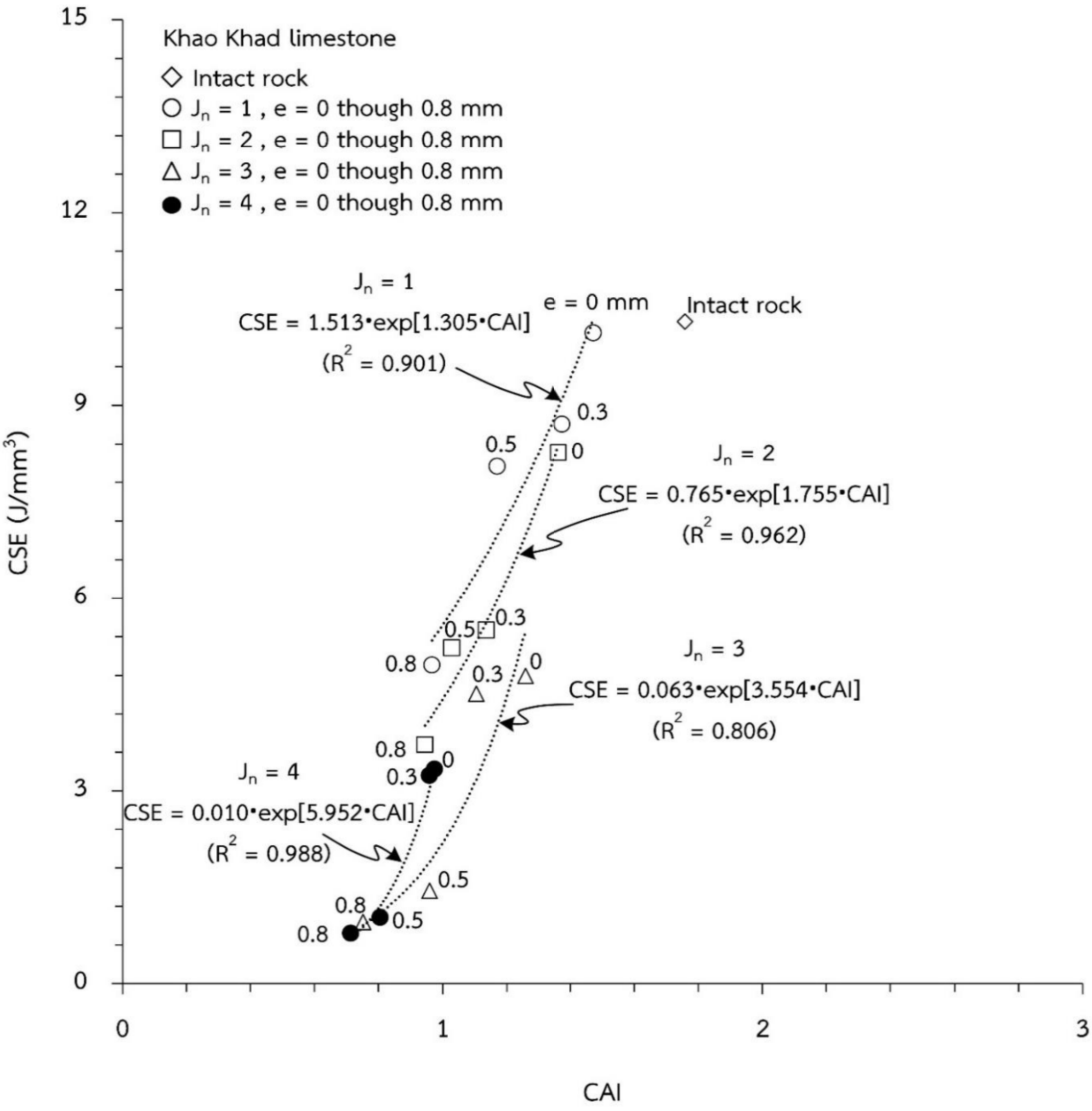

Figure 6.7 Correlation between CSE and CAI for all rock type for Khao Khad limestone.

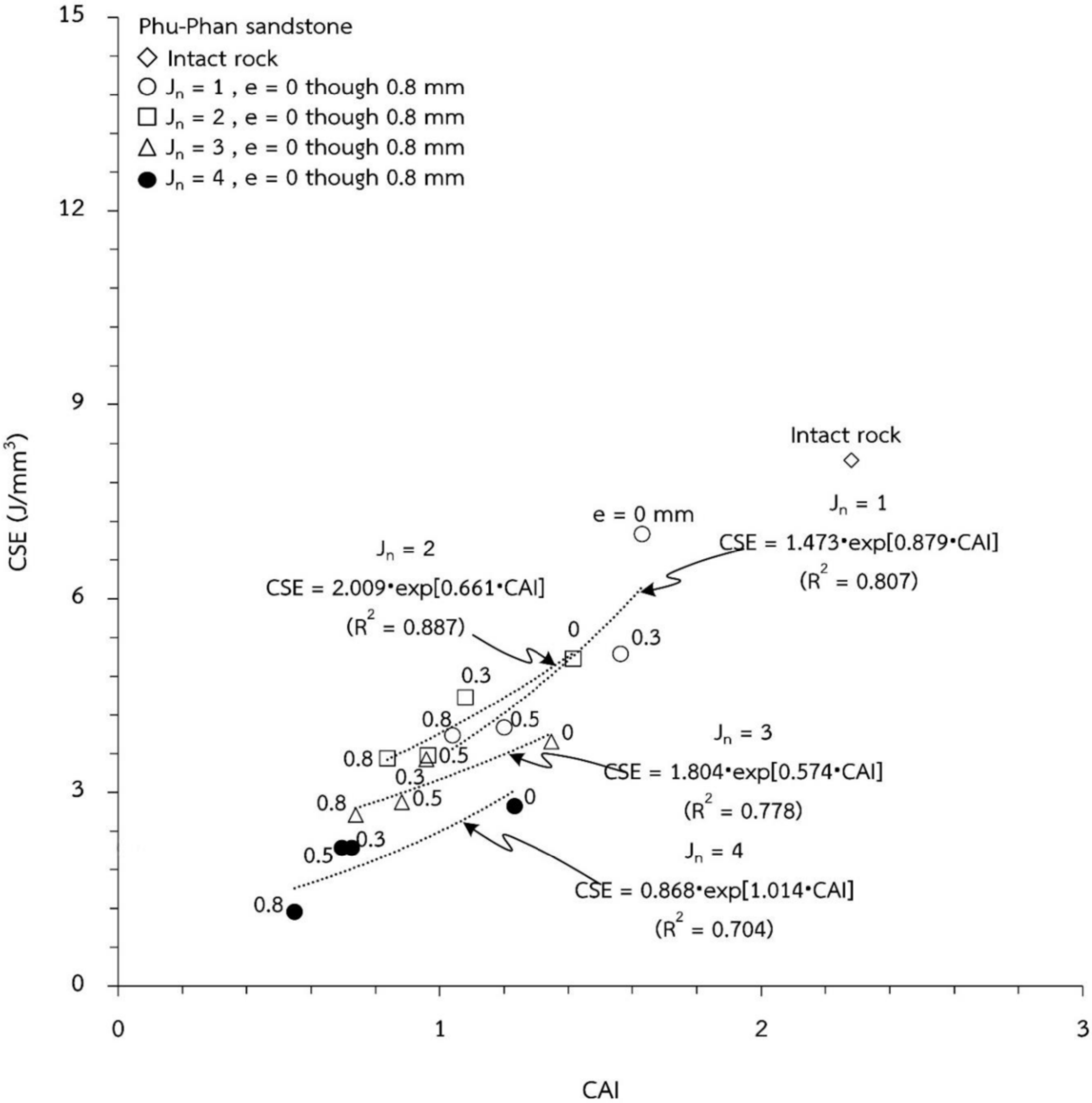

Figure 6.8 Correlation between CSE and CAI for all rock type for Phu Phan sandstone.

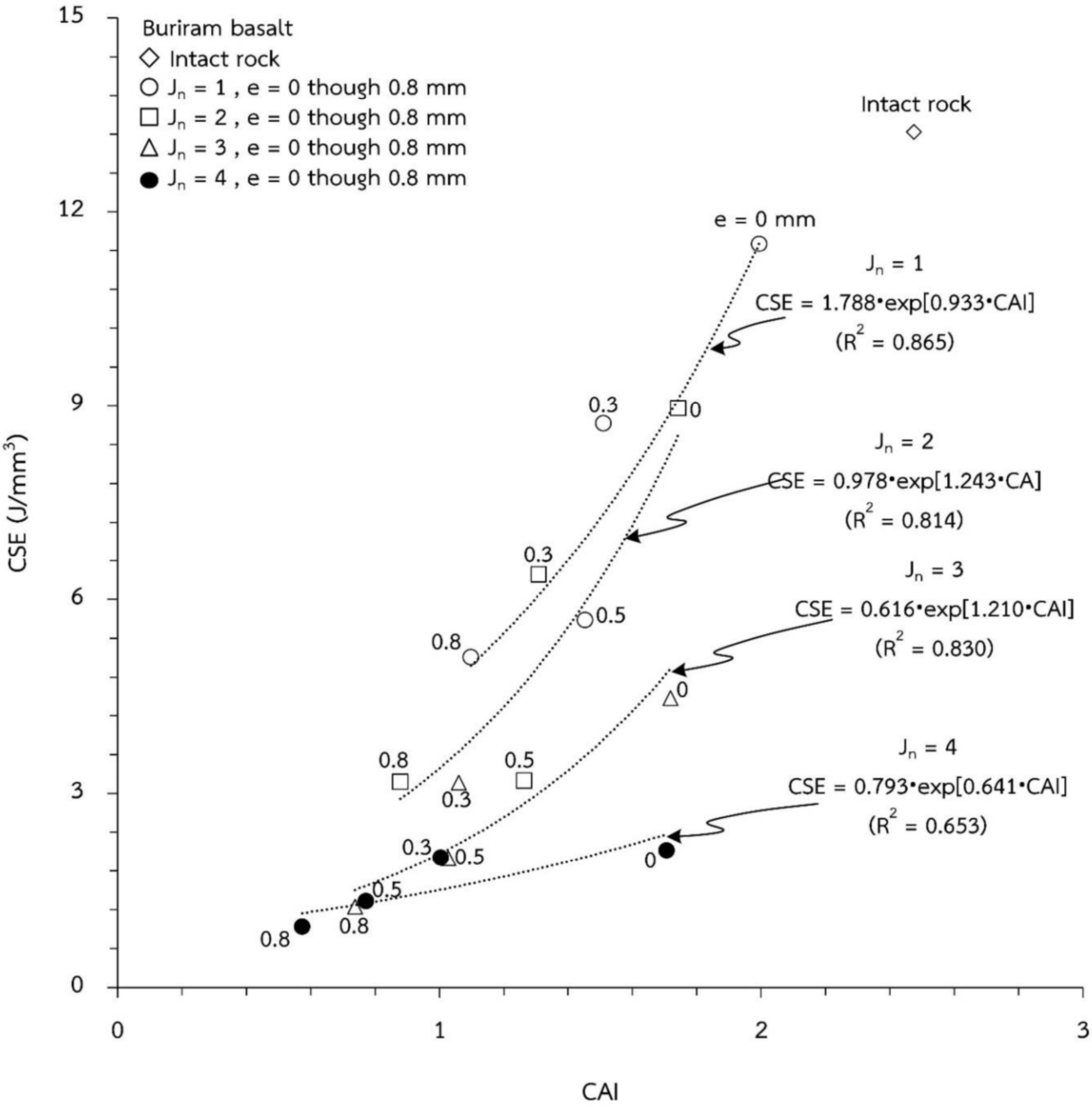

Figure 6.9 Correlation between CSE and CAI for all rock type for Buriram basalt.