CHAPTER VI
ANALYSIS OF TEST RESULTS

6.1 Introduction

This chapter analyzes the CERCHAR abrasivity index (CAI) results and its variations due to bedding plane orientations and scratching directions. The investigation focuses on the anisotropic nature of rock abrasiveness and its implications for rock cutting and excavation processes. The concept of work and energy associated with scratching forces and groove volumes is derived to assess the energy required by the steel stylus pin during the test.

6.2 CERCHAR abrasivity index

The specimens are tested under varying bedding plane orientations (α) and scratching directions (θ) to evaluate their effects on the CERCHAR abrasivity index (CAI). The results show that the CAI values show variations depending on α and θ. Figure 6.1 plots CAI as a function of α, showing different effects of bedding plane orientations for different rock types. For the well-defined bedding plane rocks (e.g. argillaceous limestone and sandstones), CAI shows the maximum value at α = 90°, where at α = 0° and 135° CAI's are highest. For the poorly defined bedding planes (bedded limestone and gypsum) CAI's slightly increases form α = 0° toward 135°. A polynomial equation is proposed to represent these relationships as:

$$\mathrm{CAI} = l_1 \cdot \alpha^2 + l_2 \cdot \alpha + l_3 \tag{6.1}$$

where l_1, l_2 and l_3 are empirical constants. Good correlations are obtained (R^2>0.8). Table 6.1 gives their numerical values.

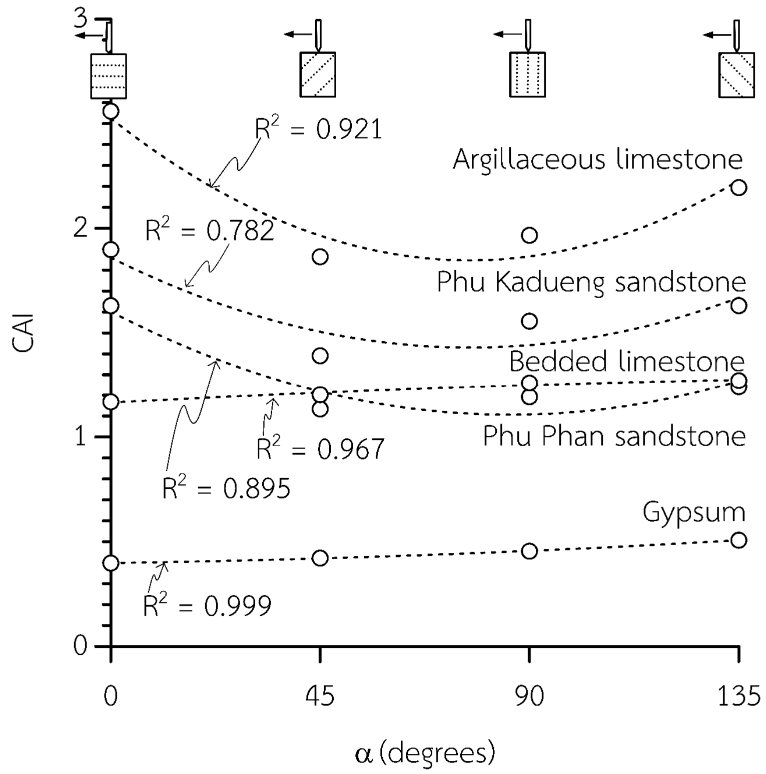

Figure 6.1 CERCHAR abrasivity index (CAI) vs functions of α, with polynomial equations.

Table 6.1 Numerical values from empirical constants l_1, l_2 and l_3 of equation 6.1.

Type	Polynomial regression equations	R^2
Khao Khad argillaceous limestone	$CAI = 1.1400 \cdot 10^{-4}\alpha^2 - 0.0176\alpha + 2.5257$	0.921
Khao Khad bedded limestone	$CAI = - 2.8148 \cdot 10^{-6}\alpha^2 - 0.0012\alpha + 1.1651$	0.967
Phu Kadueng sandstone	$CAI = 7.1778 \cdot 10^{-5}\alpha^2 - 0.1111\alpha + 1.8599$	0.782
Phu Phan sandstone	$CAI = 6.7204 \cdot 10^{-5}\alpha^2 - 0.1154\alpha + 1.6020$	0.895
Tak Fa gypsum	$CAI = 3.5185 \cdot 10^{-6}\alpha^2 - 0.0033\alpha + 0.3984$	0.999

Figure 6.2 shows CAI as a function of angle θ. For all rock types, CAI slightly increases with θ where they can be represented by a linear equation:

$$CAI = m_1 \cdot \theta + \eta_1 \quad (6.2)$$

where m_1 and η_1 are empirical constants. Good correlations are obtained ($R^2>0.9$). Their numerical values are given in Table 6.2.

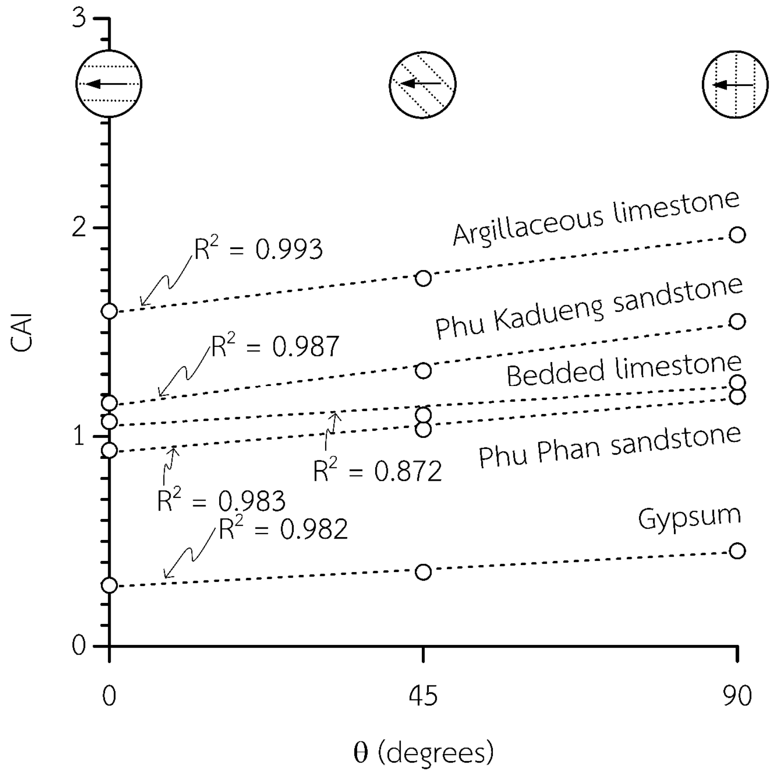

Figure 6.2 CERCHAR abrasivity index (CAI) as functions of θ, with linear equations.

Table 6.2 Numerical values from empirical constants m_1 and η_1 of equation 6.2.

Type	Linear regression equations	R^2
Khao Khad argillaceous limestone	$CAI = 0.0040 \cdot \theta + 1.5931$	0.972
Khao Khad bedded limestone	$CAI = 0.0020 \cdot \theta + 1.0508$	0.991
Phu Kadueng sandstone	$CAI = 0.0043 \cdot \theta + 1.1473$	0.994
Phu Phan sandstone	$CAI = 0.0029 \cdot \theta + 0.9253$	0.996
Tak Fa gypsum	$CAI = 0.0018 \cdot \theta + 0.2842$	0.991

6.3 Groove volume

The groove volume occurs during CERCHAR testing reflects the material removal characteristics as influenced by bedding plane orientations (α) and scratching directions (θ), Figures 6.3 plots groove volumes as functions of α, showing different effects of bedding plane orientations for different rock types. For all rock types, groove volume shows the maximum value at α about 90°, where at α = 0° and 135°, groove volume is smallest. The relationship can be described using a polynomial equation.

$$V = k_1 \cdot \alpha^2 + k_2 \cdot \alpha + k_3 \tag{6.3}$$

where k_1, k_2 and k_3 are empirical constants. Good correlations are obtained (R^2>0.8) and their numerical values are presented in Table 6.3.

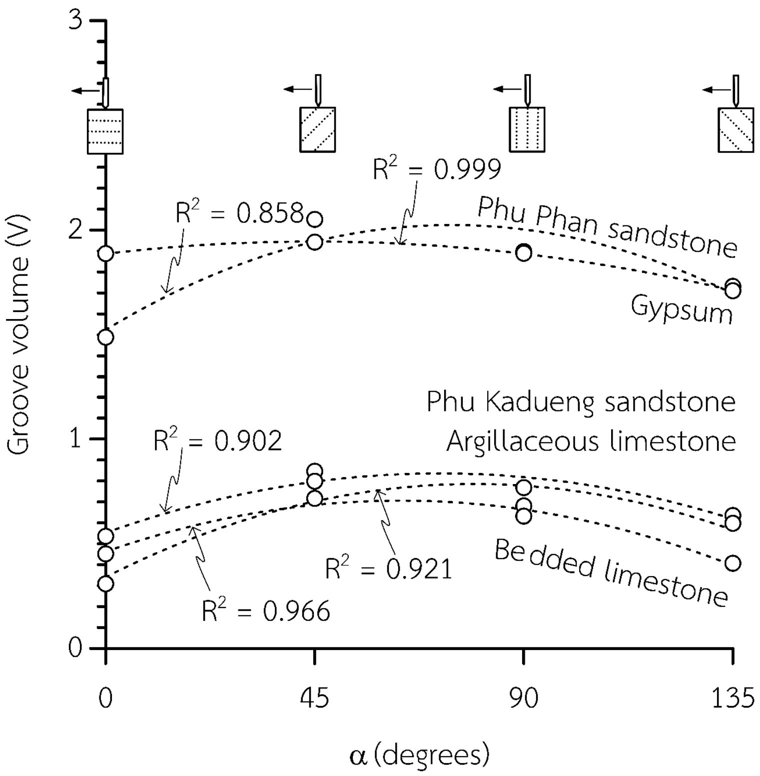

Figure 6.3 Groove volumes as functions of α, with polynomial equations.

Table 6.3 Numerical values from empirical constants k_1, k_2 and k_3 of equation 6.3.

Type rock	Polynomial regression equations	R^2
Khao Khad argillaceous limestone	$V = - 7.0755 \cdot 10^{-5}\alpha^2 - 0.0112\alpha + 0.3407$	0.842
Khao Khad bedded limestone	$V = - 6.0501 \cdot 10^{-5}\alpha^2 - 0.0077\alpha + 0.4624$	0.966
Phu Kadueng sandstone	$V = - 5.4777 \cdot 10^{-5}\alpha^2 - 0.0079\alpha + 0.5524$	0.902
Phu Phan sandstone	$V = - 8.9941 \cdot 10^{-5}\alpha^2 - 0.0134\alpha + 1.5238$	0.858
Tak Fa gypsum	$V = - 2.8778 \cdot 10^{-5}\alpha^2 - 0.0026\alpha + 1.8872$	0.999

Figure 6.4 shows groove volume as a function of θ. The results show a slight increase in groove volume with θ for all rock types, which can be represented by a linear equation:

$$V = m_2 \cdot \theta + \eta_2 \qquad (6.4)$$

where m_2 and η_2 are empirical constants. Good correlations are obtained (R^2>0.9). Their numerical values are given in Table 6.4.

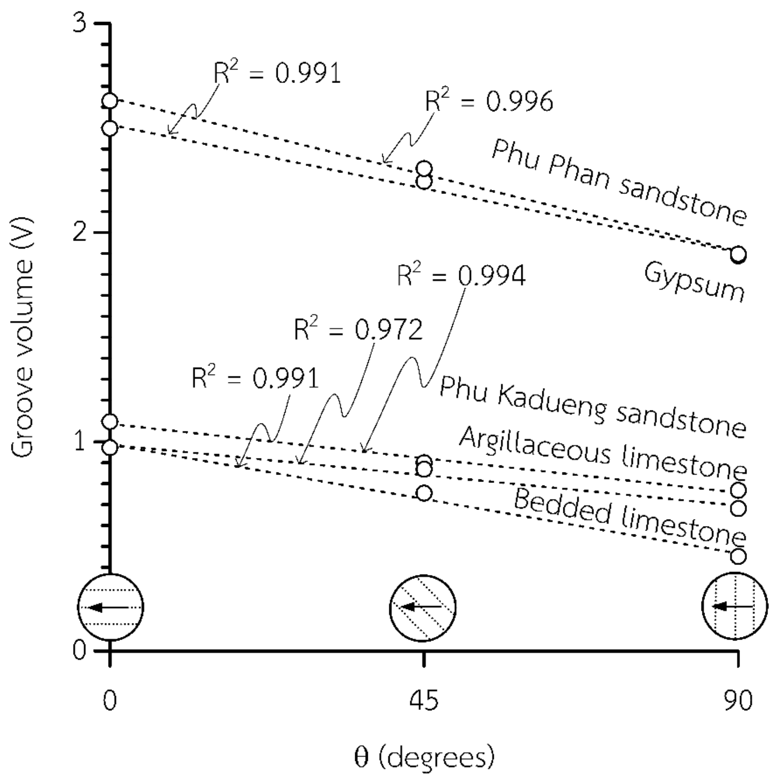

Figure 6.4 Groove volumes as functions of θ, with linear equations.

Table 6.4 Numerical values from empirical constants m_2 and η_2 of equation 6.4.

Type rock	Linear regression equations	R^2
Khao Khad argillaceous limestone	$V = - 0.0032 \cdot \theta + 0.9863$	0.972
Khao Khad bedded limestone	$V = - 0.0058 \cdot \theta + 0.9872$	0.991
Phu Kadueng sandstone	$V = - 0.0029 \cdot \theta + 0.9253$	0.994
Phu Phan sandstone	$V = - 0.0081 \cdot \theta + 2.6446$	0.996
Tak Fa gypsum	$V = - 0.0068 \cdot \theta + 2.5159$	0.991

6.4 Lateral force

The lateral force occurs during scratching provides insight into the resistance of different rock types under varying bedding plane orientations and scratching directions. Figure 6.5 and 6.6 plot lateral forces as a function of bedding plane orientations (α) and scratching directions (θ), showing different effects of bedding plane orientations for different rock types. In stronger rocks (e.g. Khao Khad argillaceous limestone), lateral force varies significantly with orientation. Softer rock (e.g. Tak Fa gypsum) shows relatively stable values across different orientations. The best-fit equations describing the force-distance F–d_s relationships for bedding plane orientations and scratching directions are presented in Equation (6.5) and summarized in Table 6.5. To describe the relationship between lateral force (F) and scratching distance (d_s) is described using an empirical model:

$$F = a \cdot (1 - \exp \cdot (-b \cdot d_s)) \qquad (6.5)$$

where a and b are empirical constants specific to each rock type. Good correlations are obtained (R^2>0.9). The numerical values of the empirical constants are provided in Table 6.5.

The lateral force is influenced by both the scratching distance and bedding plane orientations and scathing directions, the empirical constants a and b are not fixed values but instead vary as functions of α or θ. This variation accounts for directional anisotropy in rock strength and abrasiveness, allowing a more comprehensive representation of force behavior.

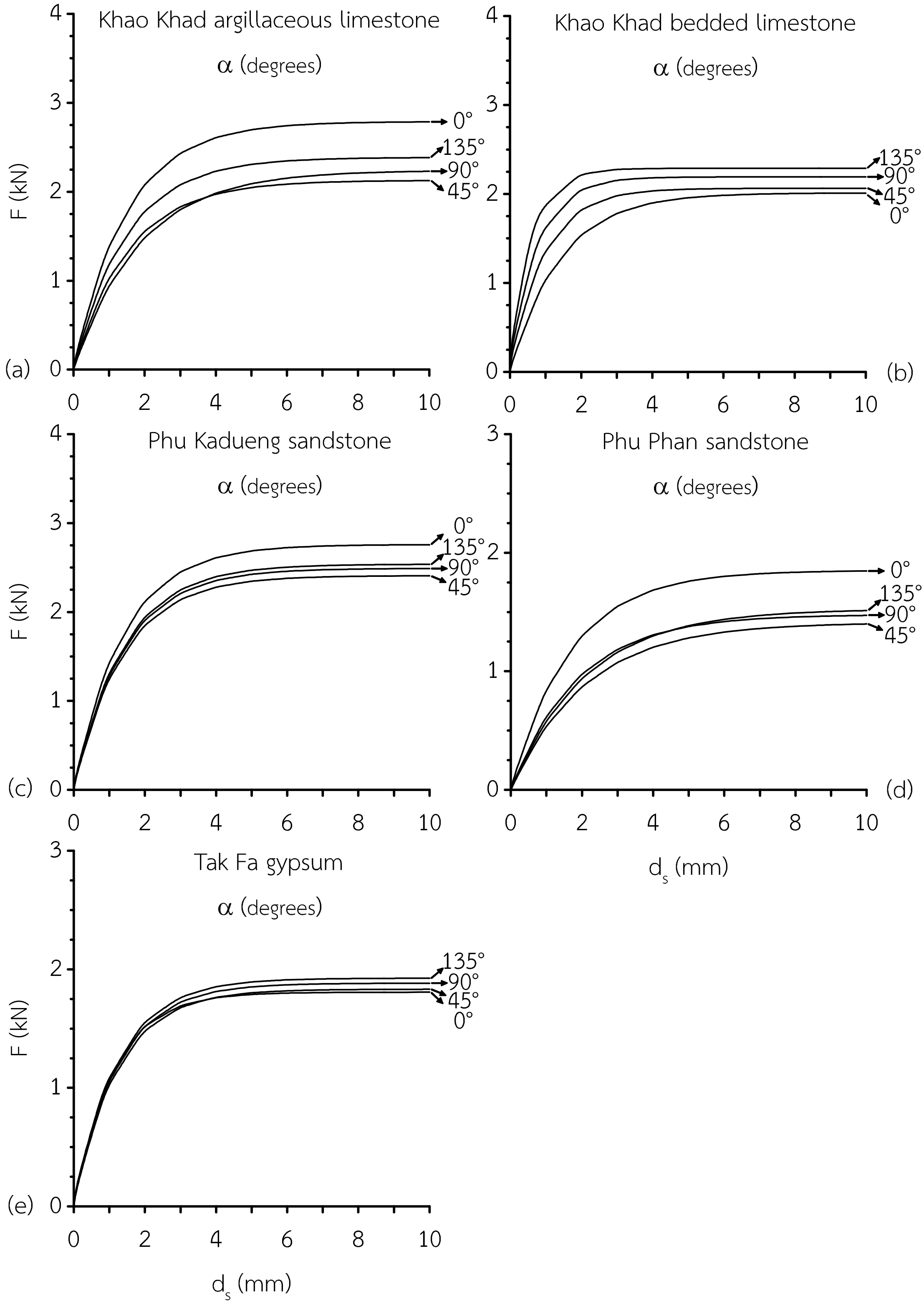

Figure 6.5 Lateral force as a function of bedding plane orientations (α).

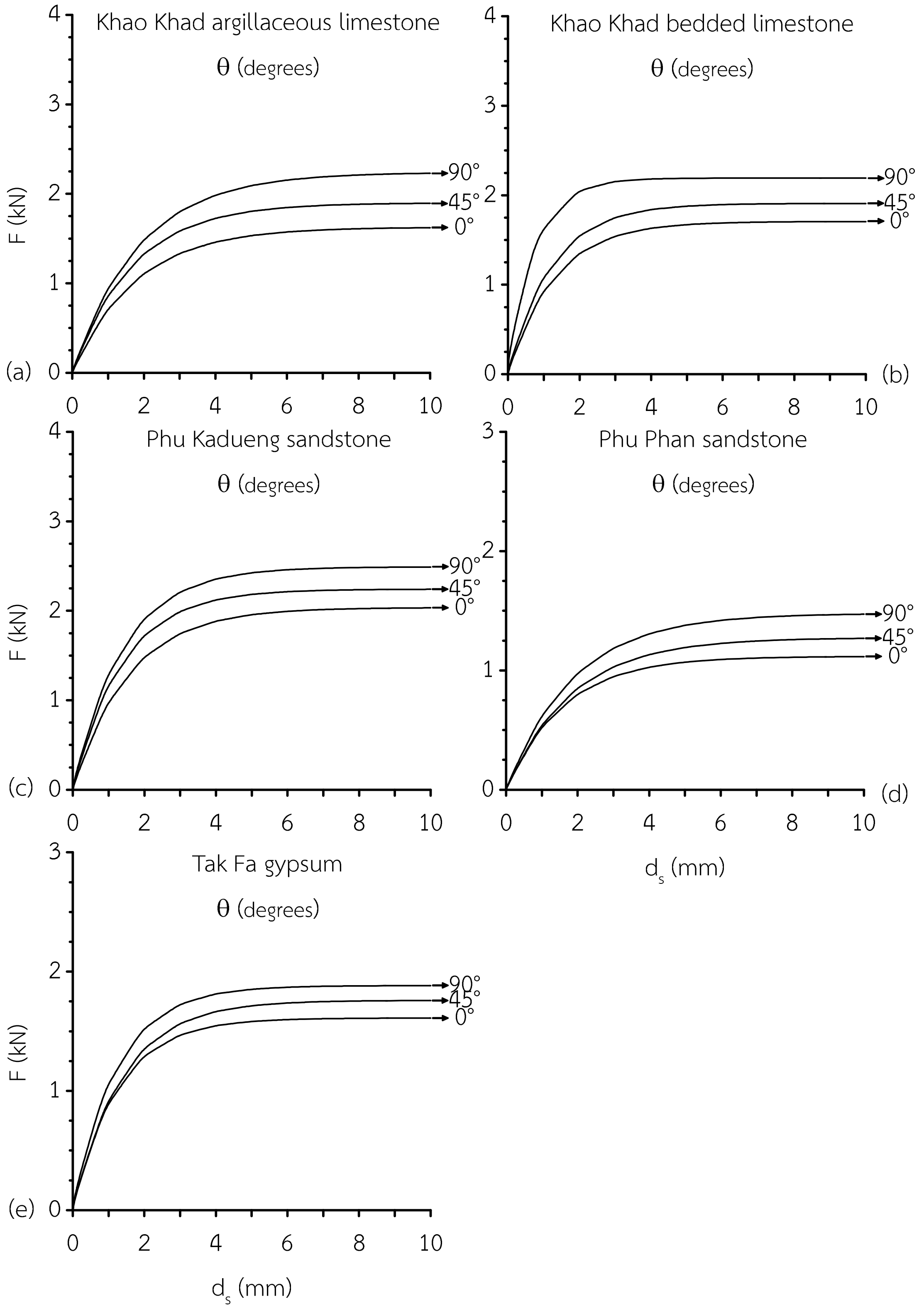

Figure 6.6 Lateral force as a function of scratching directions (θ).

Table 6.5 Empirical constants a and b for F-ds relation and R^2.

Rock type	α (degrees)	θ (degrees)	$F = a \cdot (1 - \exp \cdot (-b \cdot d_s))$		R^2
			a (N)	b (m^{-1})	
Khao Khad argillaceous limestone	0	-	2.789	0.682	0.986
	45	90	2.128	0.654	0.993
	90	0	1.627	0.568	0.950
	90	45	1.899	0.598	0.987
	90	90	2.240	0.541	0.989
	135	90	2.386	0.682	0.977
Khao Khad bedded limestone	0	-	2.012	0.719	0.979
	45	90	2.064	1.062	0.977
	90	0	1.707	0.777	0.990
	90	45	1.909	0.827	0.977
	90	90	2.192	1.339	0.970
	135	90	2.289	1.694	0.970
Phu Kadueng sandstone	0	-	2.759	0.728	0.995
	45	90	2.409	0.728	0.982
	90	0	2.036	0.646	0.989
	90	45	2.242	0.728	0.976
	90	90	2.491	0.724	0.993
	135	90	2.538	0.723	0.995
Phu Phan sandstone	0	-	1.850	0.603	0.978
	45	90	1.411	0.477	0.989
	90	0	1.118	0.626	0.974
	90	45	1.274	0.549	0.967
	90	90	1.478	0.538	0.963
	135	90	1.525	0.477	0.964
Tak Fa gypsum	0	-	1.807	0.912	0.995
	45	90	1.832	0.820	0.982
	90	0	1.611	0.802	0.960
	90	45	1.759	0.730	0.967
	90	90	1.883	0.819	0.983
	135	90	1.925	0.819	0.985

The best-fit equations describing the force-distance relationships while considering the effect of α or θ are presented in Equation (6.6 and 6.7) and summarized in Table 6.6. The force can be expressed as:

$$a\ (\alpha \text{ or } \theta) = m_3 \cdot (\alpha \text{ or } \theta) + \eta_3 \tag{6.6}$$

$$b\ (\alpha \text{ or } \theta) = m_4 \cdot (\alpha \text{ or } \theta) + \eta_4 \tag{6.7}$$

where m_3, η_3, m_4 and η_4 are empirical coefficients determined from experimental data for each rock type. The best-fit values of these parameters, obtained through regression analysis, are presented in Tables 6.6 and 6.7.

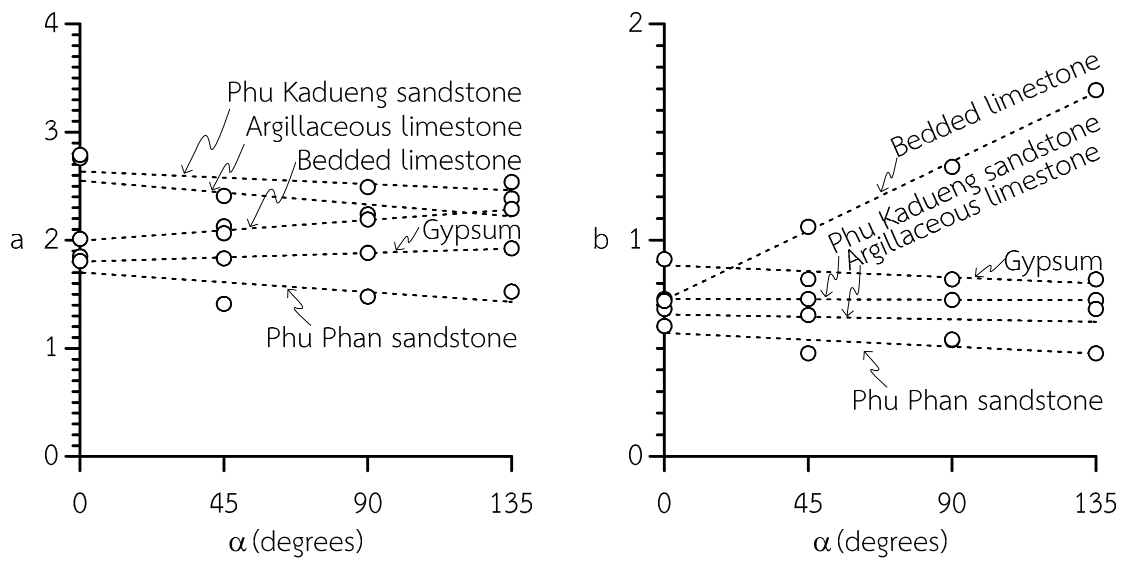

Figure 6.7 Empirical constants a (α) and b (α) for F-d_s with R^2 values by rock type.

Table 6.6 Empirical constants a (α) and b (α) for F-d_s relation and R^2.

Type rock	$F = a(\alpha) \cdot (1 - \exp \cdot (- b(\alpha) \cdot d_s))$	R^2
Khao Khad argillaceous limestone	$a(\alpha) = -0.0024 \cdot \alpha + 2.5503$	0.240
	$b(\alpha) = -0.0002 \cdot \alpha + 0.6567$	0.047
Khao Khad bedded limestone	$a(\alpha) = 0.0021 \cdot \alpha + 1.9954$	0.977
	$b(\alpha) = 0.0071 \cdot \alpha + 0.7232$	0.998
Phu Kadueng sandstone	$a(\alpha) = -0.0013 \cdot \alpha + 2.6364$	0.251
	$b(\alpha) = -0.0001 \cdot \alpha + 0.7286$	0.870
Phu Phan sandstone	$a(\alpha) = -0.0020 \cdot \alpha + 1.7022$	0.361
	$b(\alpha) = -0.0007 \cdot \alpha + 0.5713$	0.463
Tak Fa gypsum	$a(\alpha) = 0.0009 \cdot \alpha + 1.8010$	0.984
	$b(\alpha) = -0.0006 \cdot \alpha + 0.8845$	0.689

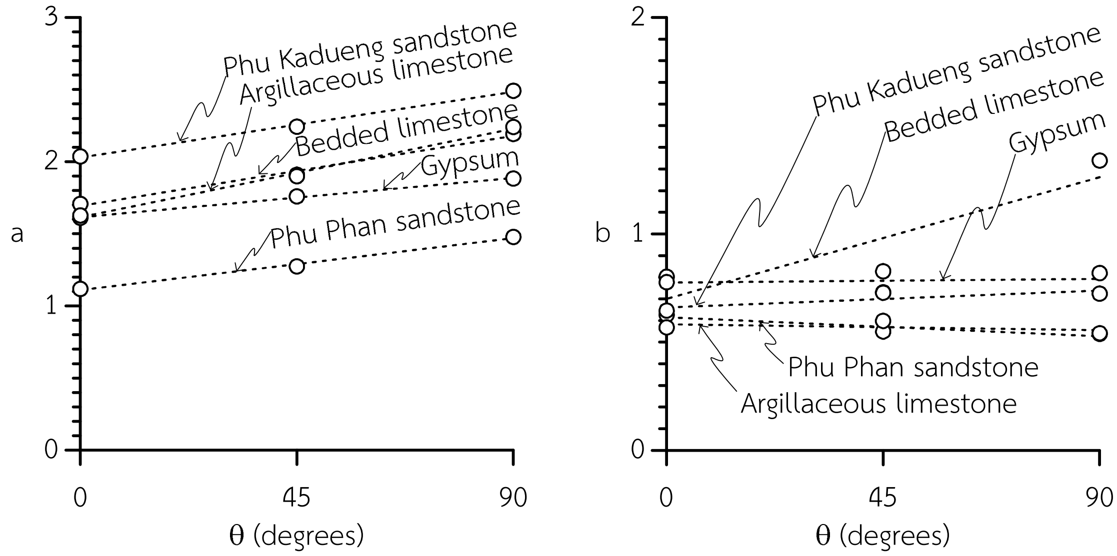

Figure 6.8 Empirical constants a (θ) and b (θ) for F-d_s with R^2 values by rock type.

Table 6.7 Empirical constants a (θ) and b (θ) for F-d_s relation and R^2.

Type rock	$F = a(\theta) \cdot (1 - \exp \cdot (-b(\theta) \cdot d_s))$	R^2
Khao Khad argillaceous limestone	$a(\theta) = 0.0068 \cdot \theta + 1.6150$	0.996
	$b(\theta) = -0.0003 \cdot \theta + 0.5825$	0.224
Khao Khad bedded limestone	$a(\theta) = 0.0054 \cdot \theta + 1.6935$	0.991
	$b(\theta) = 0.0062 \cdot \theta + 0.7000$	0.816
Phu Kadueng sandstone	$a(\theta) = 0.0051 \cdot \theta + 2.0288$	0.997
	$b(\theta) = 0.0009 \cdot \theta + 0.6603$	0.711
Phu Phan sandstone	$a(\theta) = 0.0040 \cdot \theta + 1.1100$	0.994
	$b(\theta) = -0.0009 \cdot \theta + 0.6150$	0.842
Tak Fa gypsum	$a(\theta) = 0.0030 \cdot \theta + 1.6150$	0.997
	$b(\theta) = 0.0002 \cdot \theta + 0.7752$	0.032

6.5 Work and energy

The work done (W) by the stylus during scratching is evaluated to quantify energy expenditure. Figures 6.9 and 6.10 present the work values for all tested rocks as functions of α and θ Among the tested rocks, limestones and Phu Kradueng sandstone require higher scratching energy, whereas Phu Phan sandstone and Tak Fa gypsum require low scratching energy. Table 6.8 The total work done is calculated by integrating force over the scratching path, expressed as:

$$W = \int_{d_s=0}^{10} F \cdot d_s \tag{6.8}$$

where W represents the work done by the stylus pin during the scratching.

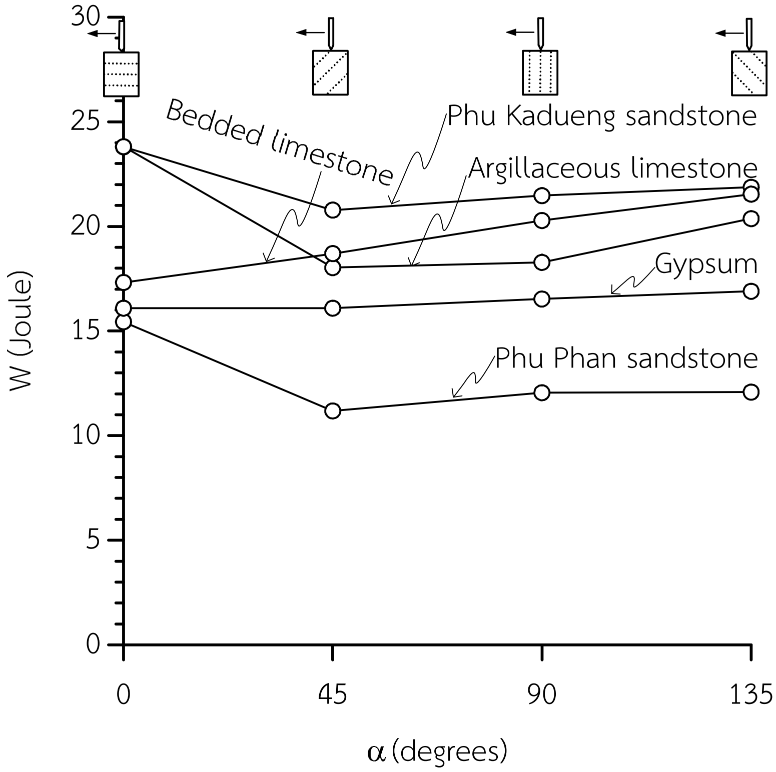

Figure 6.9 Work done as a function of bedding plane orientations (α).

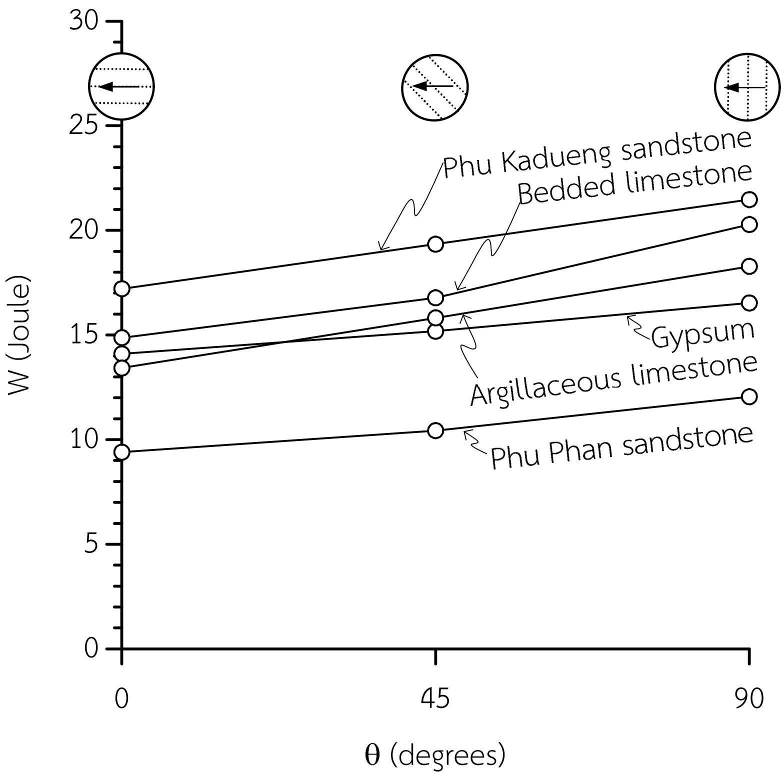

Figure 6.10 Work done as a function of scratching directions (θ).

Table 6.8 Work done for all rock tests.

Rock type	α (degrees)	θ (degrees)	W (J)
Khao Khad argillaceous limestone	0	-	23.81
	45	90	18.03
	90	0	13.42
	90	45	15.82
	90	90	18.28
	135	90	20.37
Khao Khad bedded limestone	0	-	17.32
	45	90	18.70
	90	0	14.87
	90	45	16.78
	90	90	20.28
	135	90	21.54
Phu Kadueng sandstone	0	-	23.80
	45	90	20.78
	90	0	17.21
	90	45	19.34
	90	90	21.47
	135	90	21.87
Phu Phan sandstone	0	-	15.44
	45	90	11.18
	90	0	9.40
	90	45	10.43
	90	90	12.05
	135	90	12.08
Tak Fa gypsum	0	-	16.09
	45	90	16.09
	90	0	14.10
	90	45	15.18
	90	90	16.53
	135	90	16.90

Figure 6.11 plots work energy as functions of α, showing different effects of bedding plane orientations of different rock types. For rocks with strong rocks (e.g. argillaceous limestone and sandstones), work values reach a maximum at α = 90°, where at α = 0° and 135°, work energy is lowest. For rocks with poorly defined bedding structures (e.g. bedded limestone and gypsum), work energy slightly increases from α = 0° to 135°. The relationship is represented by a polynomial equation.

$$W = e_1 \cdot \alpha^2 + e_2 \cdot \alpha + e_3 \tag{6.9}$$

where e_1, e_2 and e_3 are empirical constants. Good correlations are obtained (R^2>0.8) and their numerical values are presented in Table 6.9.

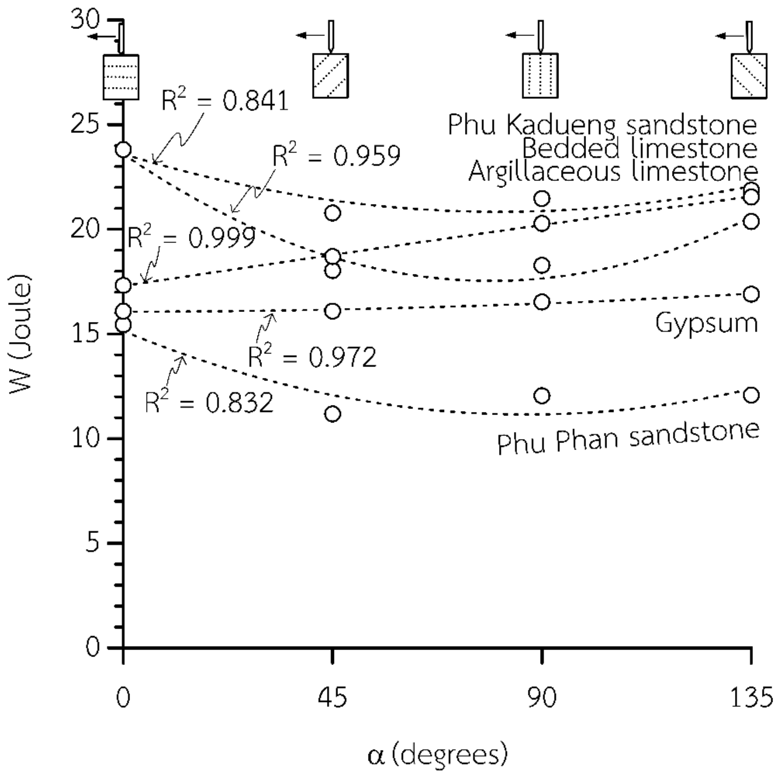

Figure 6.11 Work done as functions of α, with linear equations.

Table 6.9 Numerical values from empirical constants e1, e2 and e3 of equation 6.9.

Type rock	Polynomial regression equations	R^2
Khao Khad argillaceous limestone	$W = 9.7160 \cdot 10^{-4}\alpha^2 - 0.1535\alpha + 23.6005$	0.959
Khao Khad bedded limestone	$W = - 1.4815 \cdot 10^{-5}\alpha^2 + 0.0336\alpha + 17.2940$	0.999
Phu Kadueng sandstone	$W = 4.2220 \cdot 10^{-4}\alpha^2 - 0.0683\alpha + 23.6000$	0.841
Phu Phan sandstone	$W = 5.2960 \cdot 10^{-4}\alpha^2 - 0.0920\alpha + 15.1415$	0.832
Tak Fa gypsum	$W = 4.5679 \cdot 10^{-5}\alpha^2 + 0.0002\alpha + 16.0645$	0.972

Figure 6.12 shows work values as a function of θ. The results indicate a slight increase in work with increasing θ across all rock types. which can be represented by a linear equation:

$$W = m_5 \cdot \theta + \eta_5 \qquad (6.10)$$

where m_5 and η_5 are empirical constants. Good correlations are obtained ($R^2>0.9$). Their numerical values are given in Table 6.10.

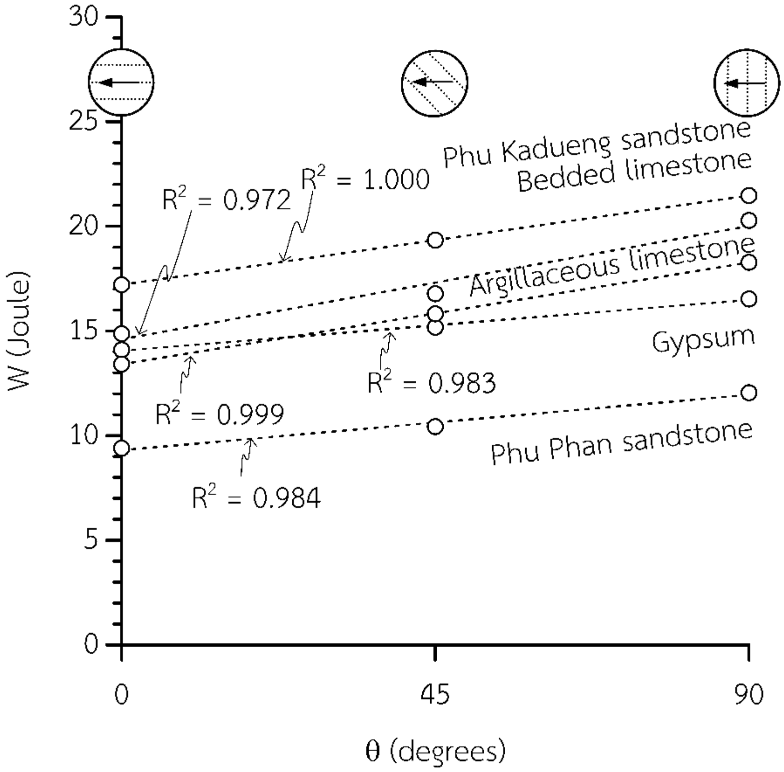

Figure 6.12 Work done as functions of θ, with linear equations.

Table 6.10 Numerical values from empirical constants m_5 and η_5 of equation 6.10.

Type rock	Linear regression equations	R^2
Khao Khad argillaceous limestone	$W = 0.0540 \cdot \theta + 13.4100$	0.999
Khao Khad bedded limestone	$W = 0.0601 \cdot \theta + 14.6050$	0.972
Phu Kadueng sandstone	$W = 0.0473 \cdot \theta + 17.2100$	1.000
Phu Phan sandstone	$W = 0.0294 \cdot \theta + 9.3017$	0.984
Tak Fa gypsum	$W = 0.0270 \cdot \theta + 14.0550$	0.996

6.6 CERCHAR Specific Energy

CERCHAR Specific Energy (CSE), a key parameter derived from the work done during scratching and the groove volume created. The effects of rock type, bedding plane orientation, and scratching direction are evaluated to provide insights into energy dynamics during rock scratching. Figure 6.13 shows CSE as a function of bedding planes and scratching directions, it is calculated by normalizing the work done by the groove volume (V), as expressed in Equation:

$$\mathrm{CSE} = \frac{W}{V} = \frac{\int_{d_s=0}^{10} F \cdot d_s}{V} \tag{6.11}$$

where V represents the groove volume created during scratching. By integrating the lateral force over the scratching distance and incorporating the groove volume, CSE provides a quantitative measure of energy expenditure for rock scratching, offering insights into material behavior and tool-rock interactions.

The analysis of CERCHAR Specific Energy (CSE) values, as summarized in Table 6.11, reveals that specific energy of scratching on rock, bedding plane orientations (α) and scratching directions (θ) significantly influence energy expenditure during scratching. Stronger rocks (e.g. Khao Khad argillaceous limestone and Phu Kadueng sandstone), show higher CSE values due to higher lateral forces and smaller groove volumes, whereas softer rocks (e.g. Tak Fa gypsum and Phu Phan sandstone) show lower CSE values, reflecting lower energy consumption per unit material removed. Scratching perpendicular to the bedding plane (θ = 90°) consistently produces the highest CSE values across all rock types, as observed in Khao Khad argillaceous limestone and Phu Kadueng sandstone, owing to increased resistance, while parallel scratching (θ = 0°) results in the lowest CSE values, particularly in Phu Phan sandstone. Bedding plane orientation (α) further amplifies this trend, with CSE values increasing as the angle of the bedding plane changes from 45° to 135°. Groove volume inversely correlates with CSE and lateral force, indicating that energy efficiency improves with increased material removal.

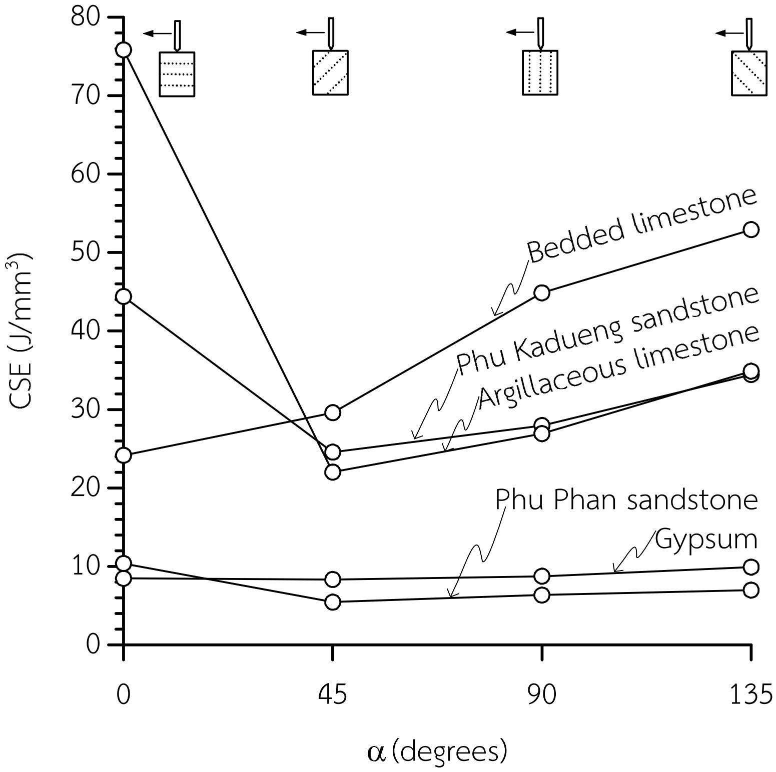

Figure 6.13 CSE as a function of bedding plane orientations (α).

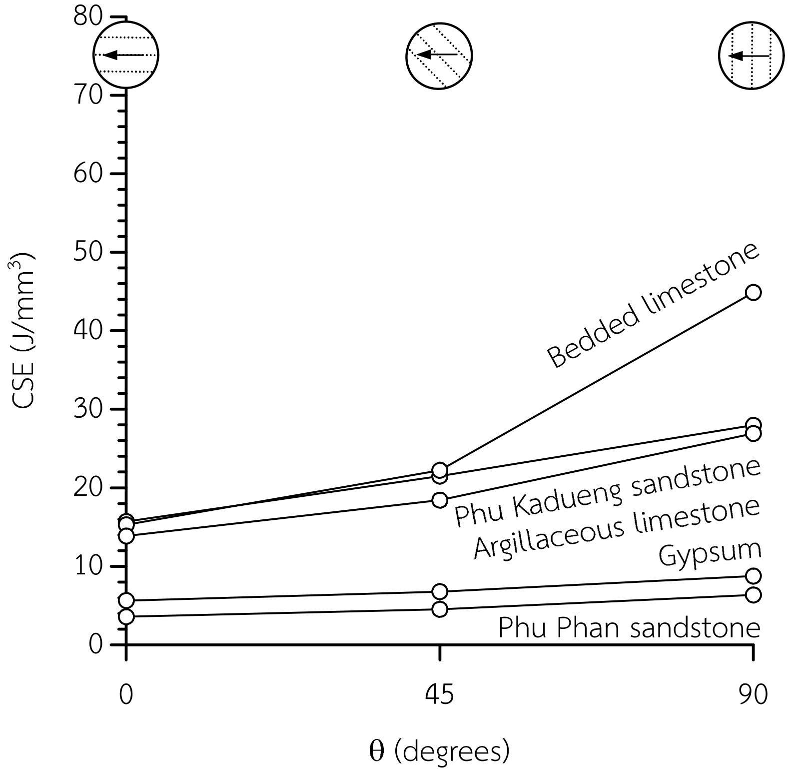

Figure 6.14 CSE as a function of scratching directions (θ).

Table 6.11 CERCHAR specific energy for all rock tests.

Rock type	α (degrees)	θ (degrees)	$F = a \cdot (1 - \exp \cdot (-b \cdot d_s))$		R^2
			a	b	
Khao Khad argillaceous limestone	0	-	2.789	0.682	0.986
	45	90	2.128	0.654	0.993
	90	0	1.627	0.568	0.950
	90	45	1.899	0.598	0.987
	90	90	2.240	0.541	0.989
	135	90	2.386	0.682	0.977
Khao Khad bedded limestone	0	-	2.012	0.719	0.979
	45	90	2.064	1.062	0.977
	90	0	1.707	0.777	0.990
	90	45	1.909	0.827	0.977
	90	90	2.192	1.339	0.970
	135	90	2.289	1.694	0.970
Phu Kadueng Sandstone	0	-	2.759	0.728	0.995
	45	90	2.409	0.728	0.982
	90	0	2.036	0.646	0.989
	90	45	2.242	0.728	0.976
	90	90	2.491	0.724	0.993
	135	90	2.538	0.723	0.995
Phu Phan Sandstone	0	-	1.850	0.603	0.978
	45	90	1.411	0.477	0.989
	90	0	1.118	0.626	0.974
	90	45	1.274	0.549	0.967
	90	90	1.478	0.538	0.963
	135	90	1.525	0.477	0.964
Tak Fa gypsum	0	-	1.807	0.912	0.995
	45	90	1.832	0.820	0.982
	90	0	1.611	0.802	0.960
	90	45	1.759	0.730	0.967
	90	90	1.883	0.819	0.983
	135	90	1.925	0.819	0.985

These relationships can be represented by a polynomial equation:

$$CSE = g_1 \cdot \alpha^2 + g_2 \cdot \alpha + g_3 \tag{6.12}$$

where g1, g2, and g3 are empirical constants. Good correlations are obtained ($R^2 > 0.9$). Their numerical values are presented in Table 6.12.

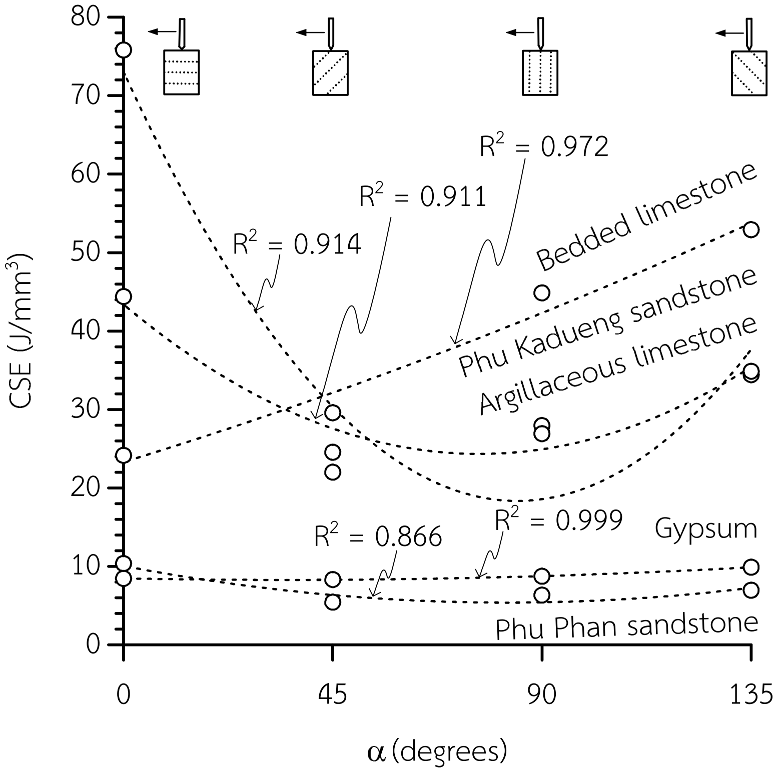

Figure 6.15 CSE as a function of bedding plane orientations (α), with polynomial equations.

Table 6.12 Numerical values from empirical constants g_1, g_2 and g_3 of equation 6.12.

Type rock	Polynomial regression equations	R^2
Khao Khad argillaceous limestone	$CSE = 0.0076\alpha^2 - 1.2916\alpha + 73.0445$	0.914
Khao Khad bedded limestone	$CSE = 0.0032\alpha^2 + 0.1820\alpha + 23.3028$	0.972
Phu Kadueng sandstone	$CSE = 0.0032\alpha^2 - 0.4976\alpha + 43.3959$	0.911
Phu Phan sandstone	$CSE = 0.0007\alpha^2 - 0.1130\alpha + 10.0650$	0.866
Tak Fa gypsum	$CSE = 0.0002\alpha^2 + 0.1111\alpha + 8.4818$	0.999

Figure 6.14 shows CSE as a function of θ. For all rock types, CSE generally increases with θ, where the relationship can be represented by a linear equation:

$$CSE = m_6 \cdot \theta + \eta_6 \qquad (6.13)$$

where m_4 and η_4 are empirical constants. Good correlations are obtained (R^2>0.9). Their numerical values are provided in Table 6.13

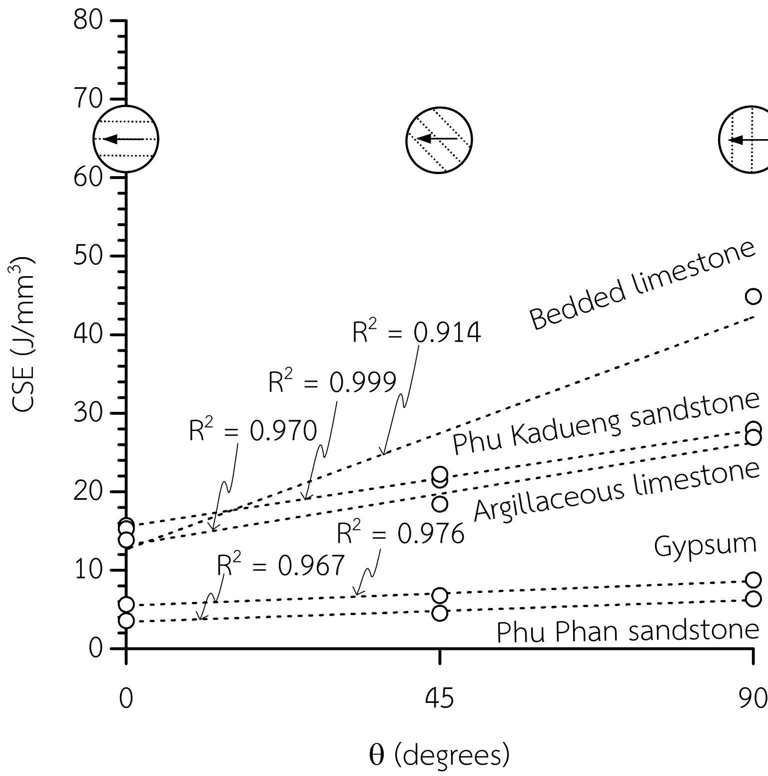

Figure 6.16 CSE as a function of scratching directions (θ), with linear equations.

Table 6.13 Numerical values from empirical constants m_6 and η_6 of equation 6.13.

Type rock	Linear regression equations	R^2
Khao Khad argillaceous limestone	$CSE = 0.1452 \cdot \theta + 13.1930$	0.970
Khao Khad bedded limestone	$CSE = 0.3287 \cdot \theta + 12.6660$	0.914
Phu Kadueng sandstone	$CSE = 0.1363 \cdot \theta + 15.5772$	0.999
Phu Phan sandstone	$CSE = 0.0308 \cdot \theta + 3.4273$	0.967
Tak Fa gypsum	$CSE = 0.0346 \cdot \theta + 5.4956$	0.976