CHAPTER VII

ENERGY CONSUMPTION

An attempt is made here to determine the energy required to reduce the fragment sizes from the initial condition to be less than 2 mm, i.e., all materials passing through the drum openings. The energy defined in this study relates to the kinetic energy used by rocks during drum rotation. This induces rolling of each fragment, leading to the scrubbing and colliding processes between the fragments and between fragments and inner drum surface (Figure 7.1). Further uses of this energy application are discussed in the following chapter.

7.1 Kinetic energy

On fragment kinetics, the relation of forces reflect their rotating motions with variation of angular velocity depending on rock mass. Rock materials can be losed depending on the amounts of time use for fragments to completely disintegrate their sizes, where less than 2 mm sizes of fragments passing through the drum. The slake durability device forces the rotation of fragments with a constant of acceleration. The device parameters are summarized in Table 7.1. Once testing drums rotate for one revolution, two mechanisms occur: (1) the collision between fragments, and (2) the scrubbing between fragments and drum surface (Figure 7.1). The energy consumed by one rock fragment for one revolution can be calculated as (Meriam & Kraige, 1980a, 1980b):

$$E_i = (1/2) I_i \cdot \omega_i^2 \qquad (7.1)$$

where E_i is rotational kinetic energy (J), I_i is moment of inertia (kg·m^2), ω_i is angular velocity (rad/s), and i is the number of test cycle (varied from 1 to 80). The moment of inertia is obtained by:

$$I_i = (2/5)m_i \cdot r_i^2 \qquad (7.2)$$

where m_i is fragment mass during drum rotation (kg) and r_i is equivalent radius of fragment under dry testing (m).

The masses of rock fragment for each test cycle are different between dry and wet conditions, where the dry fragment mass can be obtained directly from the measurements at the end of each test cycle. For wet testing, the rock fragment is submerged under water in the trough. Its mass (weight) can be obtained by subtracting the dry mass by the buoyancy force (mass of water with the same volume):

$$m_{i,\,wet} = m_i - (V_i \cdot \rho_w) \qquad (7.3)$$

where V_i is equivalent volume of fragment at test cycle i (cc) and ρ_w is density of water (g/cc).

The equivalent radius, r_i, can be obtained from the size measurements (Figure 5.4). For example, at initial condition, the equivalent radius is represented by r_0 (i=0) which is equal to 17.37 mm $\{[(28\times28\times28)\cdot(3/4\pi)]^{1/3}\}$. The equivalent volume, V_i, is a representative spherical volume which can be calculated from r_i. Assuming that there is no sliding between fragment surfaces and inner drum surface, the angular velocity of fragment (ω_i) is equal to that of the drum:

$$\omega_i = v_d/r_d \qquad (7.4)$$

where v_d is linear velocity of drum (m/s) and r_d is inner drum radius (m). For one drum revolution, the number of fragment revolutions (R_i) at test cycle i can be calculated by:

$$R_i = r_d/r_i \tag{7.5}$$

where r_d is inner drum radius which is constant equal to 0.07 m. As a result, the energy used by a fragment for one drum revolution becomes:

$$E_i = [(1/2)\, I_i \cdot \omega_i] \cdot R_i \tag{7.6}$$

And for one test cycle (2,000 drum revolutions):

$$E_i = [(1/2)\, I_i \cdot \omega_i^2] \cdot R_i \cdot 2{,}000 \tag{7.7}$$

The accumerated energy from test cycles 1 to 80 is

$$E = \sum_{i=1}^{80} E_i \tag{7.8}$$

The energy results are plotted as a function of test cycle in Figure 7.2. The diagrams show that rock fragments tested under wet condition consume energy less than those under dry condition. This is primarily because their submerged weight is about 40% less than their dry weight, and results in a reduction of the moment of inertia. The highest energy is used by dry PPCS specimens (Figure 7.2b) as they have higher density (fragment mass) than the other two sandstones.

Even though the input energy from drum rotation is constant from test cycles 1 to 80, the energy consumed by rock fragments decrease with their sizes, as suggested by non-linear curves of accumulated energy (E) as a function of test cycle (N) in Figure 7.2. Their relation can be best described by a power equation:

$$E = A \cdot \mathrm{N}^{\mathrm{B}} \tag{7.9}$$

where *A* and *B* are empirical constants whose numerical values are given in the figure. The good correlations are obtained (R^2>0.9). Equation (7.9) allows predicting the energy that rock fragments consume to become 2 mm or less. By substituting the numbers of test cycles required to obtain 100% passing given in section 6.3, the energy required for each sandstone type and test condition can be calculated.

The results are given in Table 7.2. Disintegration of dry fragments consumes more kinetic energy than that of water submerged fragments. PPCS specimen shows the highest energy consumption than the other two sanstones. Water penetration decreases its kinetic energy used to reduce the fragment size. The discrepansies of the accumulated energy magnitudes between dry and wet testing reflect the role of water penetration. This explains why the PPCS and PPSS specimens show significant differences in energy consumptions between wet and dry, while the water-insensitive PWSS specimens show comparable energy.

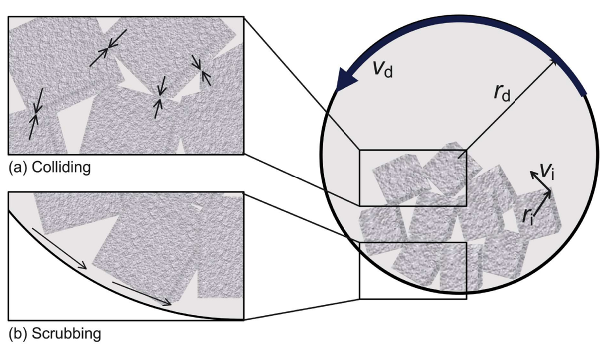

Figure 7.1 Scrubbing and colliding processes between fragments (a) and between fragments and inner drum surface (b).

Table 7.1 Parameters for testing drum.

Parameters	Dimensions	Length (m)	0.10
		Diameter (m)	0.14
	Velocity (m/s)		0.147
	Mass (kg)		0.6

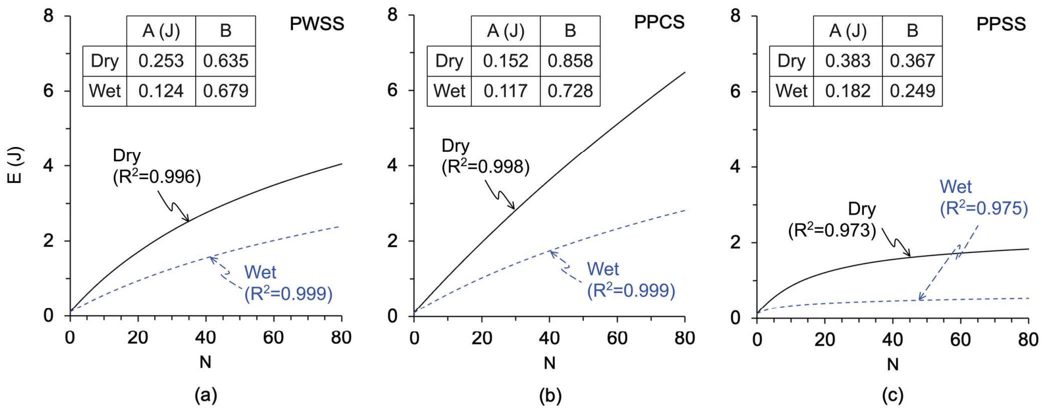

Figure 7.2 Accumulated energy (*E*) as a function of test cycle (N). Dry and wet testing shown as solid lines and dash lines. They are fitted by $E=A{\cdot}N^B$.

Table 7.2 Prediction of accumulated energy (*E*) and test cycle (*N*) required to obtain 100% passing materials with 2 mm or less.

Rock type	Condition	N	E (J)
PWSS	Dry	219	9.08
	Wet	391	7.14
PPCS	Dry	454	34.02
	Wet	257	9.64
PPSS	Dry	135	2.90
	Wet	116	0.87

7.2 Erosive energy

Figure 7.2 shows the relative of energy for each rock that changed their volumes to the specific sizes. The power equation (7.9) that generally fitted the results through a function of test cycles (Figure 7.2) can transform as a function of equivalent radius, r_i, where each of those values obtained from equation (7.2). The specific energy using for each condition of rocks degraded to interesting radius can be expressed as:

$$E_s = A \cdot e^{rB} \tag{7.10}$$

where E_s represents the specific energy (J), r_i is the interesting radius (mm), and A and B are the constant parameters as shown in Table 7.3. Good correlations are obtained (R^2>0.9). For three rock types, it seem that PPCS specimens under wet condition uses a higher energy than those of others, as the erosive energy tend to increase while having a larger sizes. However, the turning points might be when rocks have a radius around 17 mm, where PPCS specimens continuing with a lower rate of degradation. To specify the amount of energy between two sizes of rocks. The following equation is proposed:

$$E = \int_0^1 (A \cdot e^{Br})\, dr \tag{7.11}$$

and hence;

$$E = (A/B) \cdot (e^{Br_0} - e^{Br_1}) \tag{7.12}$$

Figure 7.4 represents only the accumulated energy that has the initial radius of 40 mm. The diagram in Figure 7.4 also are included with the international standards for each fragment from cobbles to sands. The accumulated energy for PPSS specimen with initial radius of 40 mm (cobble size, UCSC) under wet condition disintegrated to the smaller sizes are illustrated in Figure 7.5.

Table 7.3 Constant parameters using in equation (7.10) through (7.12).

Parameters	PWSS		PWCS		PPSS	
	Dry	Wet	Dry	Wet	Dry	Wet
A	$7.69{\cdot}10^{-5}$	$3.63{\cdot}10^{-5}$	$1.24{\cdot}10^{-5}$	$5.96{\cdot}10^{-5}$	$2.06{\cdot}10^{-4}$	$6.10{\cdot}10^{-4}$
B	0.4113	0.4620	0.5185	0.6914	0.3348	0.2467

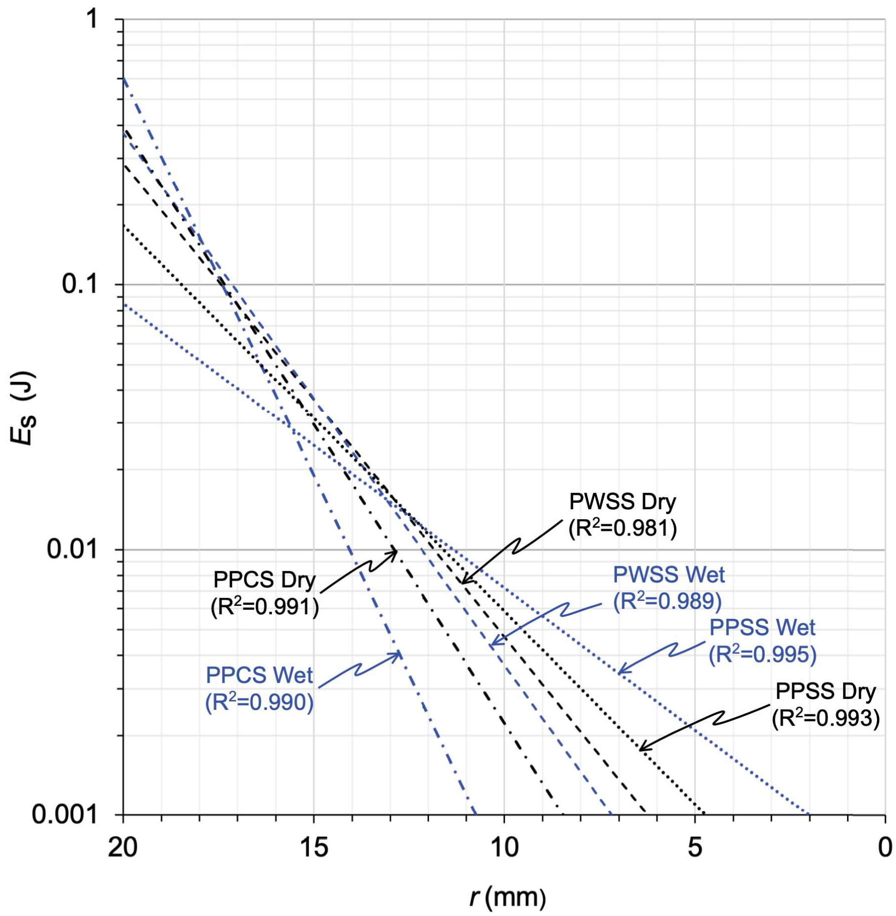

Figure 7.3 Specific energy for PWSS, PPCS and PPSS specimens as a function of equivalent radius (r_i).

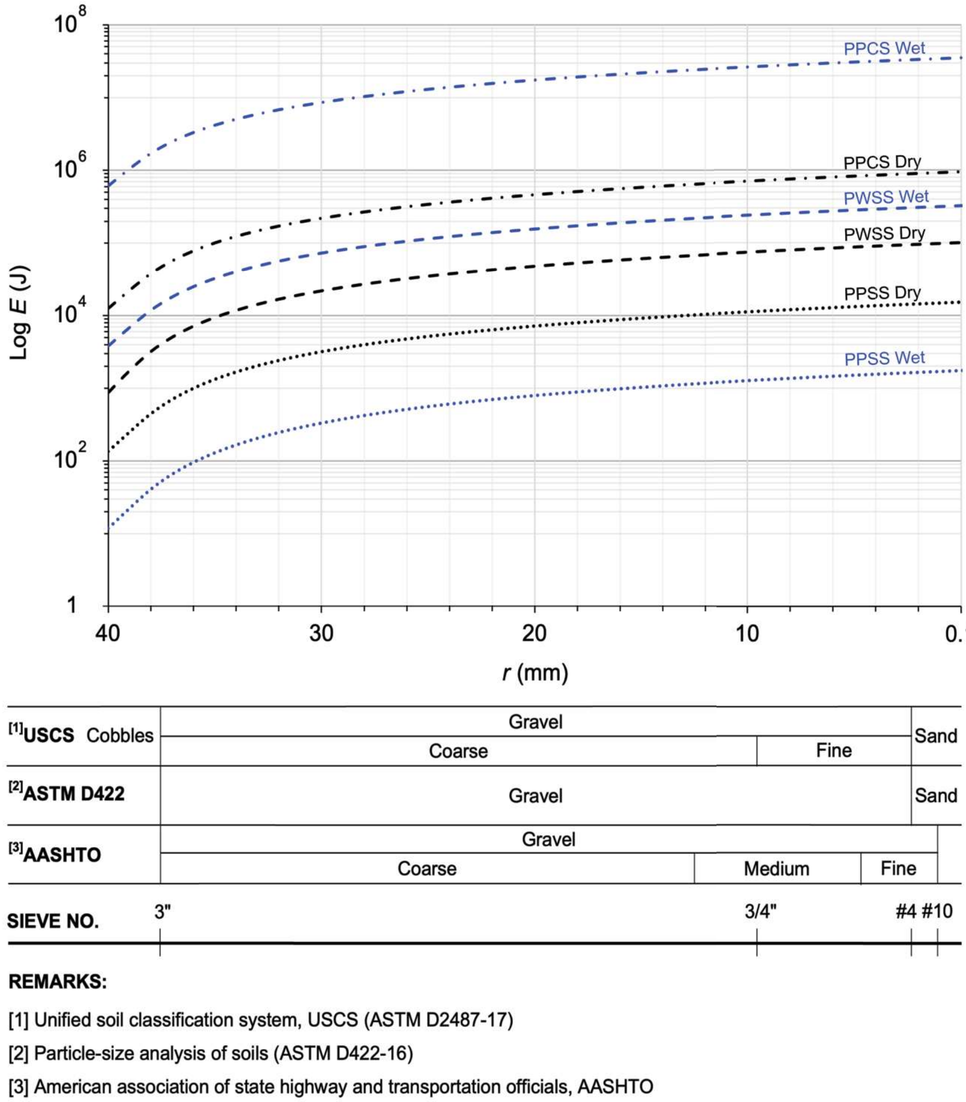

Figure 7.4 Accumulated Energy for PWSS, PPCS, and PPSS specimens with cobbles disintegrated to smaller sizes.

r = 150.0 | 37.5 | 9.5 | 2.375 | 1.0 | 0.213 | 0.038

		Cobble	Gravel			Sand		Fines
			Coarse	Fine	Coarse	Medium	Fine	
Cobble			29178 × 10^9					
Gravel	Coarse			25.7423	25.7636	25.7649	25.7654	25.7655
	Fine				0.0213	0.0226	0.0232	0.0234
Sand	Coarse					0.0013	0.0018	0.0019
	Medium						0.00056	0.00067
	Fine							0.00011

Figure 7.5 Energy for PPSS specimens under wet condition to disintegrate as a smaller sizes, The classification is followed the unified soil classification system, USCS (ASTM, D2487-17).