receive stress and their ability to provide sufficient stress for breakage to occur. These breakage parameters generally increase with particle size – larger particles are both weaker and easier to find.

Grinding systems that involve a significant contribution from the attrition mechanism (chipping or abrasion) produce quite different breakage rate and breakage distribution relationships. Rates appear to decrease with time, or perhaps more correctly, with the degree of attrition. The gradual removal of prominent protrusions leads to a rounding of particles and increased resistance to further attrition (Tangsripongkul, 1993). Breakage distributions show a bimodal character as illustrated in Figure 9.1. The bimodal form is also reflected in the product size distributions – the existence of such forms provides evidence that attrition plays a prominent role in the grinding process. Such distributions are shown for chocolate refining (Peter, 1994). Similar effects can occur due to variation in the relative strength of the feed particles such that energy input is sufficient to break some, but not all, of the particles. Those particles that do break produce smaller fragments that are readily broken further. Such is the case when sugar and whole milk powder are refined together.

Particle size reduction is very energy intensive, with the energy requirements increasing as the average size becomes smaller. Equation 9.1 is often referred to as the general law of comminution and is the basis for more specific relationships, for example Rittinger's Law ($n = 2$), Kick's Law ($n = 1$) and Bond's Law ($n = 3/2$),

$$\frac{dE}{dx} = -\frac{K}{x^n} \tag{9.1}$$

where dE is the change in energy, dx is the change in size, K is a constant and x is particle size. Fritzsche (1994) in fact demonstrated an exponential increase in specific energy requirements for refining milk chocolate mass as the particle size was reduced. Kuster (1984) presented similar data for grinding cocoa mass, particularly in the size range below 20 μm (8×10^{-4} in).

Breakage of brittle materials is essentially an irreversible process. However, in the case of softer, more plastic substances, agglomeration of the fragments can be significant. In contrast to breakage rates, which generally decrease with decreasing particle size, agglomeration rates and agglomerate strength tend to be higher for smaller particles (Rumpf, 1962). The net effect of simultaneous breakage and agglomeration is an approach to a limiting size at which the growth and breakage rates are equal. The structure of agglomerates differs from that of the original solid particles, so that breakage behaviour can also be expected to be different. In particular, agglomerates tend to be weaker and more plastic than the solid particles. An important consequence is that breakage rates decrease as the solid particles are broken down and then converted into agglomerates, which leads to a situation in which the average particle size first decreases and then begins to increase. At the same time, the size distribution becomes narrower as the fine particles are eliminated by agglomeration (Kaya *et al.*, 1997). It is likely that some agglomeration is taking place at the end stages of chocolate refining, and that conching, in part, disperses these agglomerates, although new agglomerates can also form due to moisture "sticking " particles together (see Chapter 10).

The physical and chemical environment in a grinding device is known to affect grinding. Wet grinding is often considered to be more "efficient" than dry grinding (Bond, 1960). It seems that the primary effects are on the agglomeration of fine particles, since the use of liquids permits greater control over particle dispersion. Chemical additives like surfactants, so-called grinding aids, are believed to function largely through their effects on dispersion and rheology (Klimpel and Manfroy, 1978). Powder slurry rheology is clearly a critical factor in fine-grinding operations. Unfortunately, current understanding of the relationship between particle dispersion and rheology, especially important in conching operations, is rather limited.

9.3 Grinding equipment

The choice of equipment for size reduction depends on many factors, including the feed particle size, the type of material being processed, the final particle size and, as we have discussed, the role the operation plays in the integrated system. It is not surprising that a wide variety of size reduction operations are in use in chocolate and cocoa processing plants. Despite wide differences in the nature and characteristics of the materials being ground, the types of equipment used in industrial applications are remarkably similar.

9.3.1 Crushers

Crushers apply direct mechanical force (primarily compressive) to individual particles or compacted beds. Roll refiners used in chocolate manufacture fall into this category. Machines of this type are relatively efficient in terms of utilisation of energy input. However, their effectiveness tends to fall off drastically in applications to very fine grinding. Individual particle crushing becomes impractical at such sizes and energy is wasted in bed compaction. Disc mills and roll refiners incorporate shear as well as compression in the grinding action and are most effective for brittle materials.

9.3.2 Media mills

The grinding action in media mills is provided by the relative motion of individual loose elements, the grinding media, which may consist of balls, rods or beads. Particle placement is essentially random; stress is applied only to those particles that happen to be caught in contact between media elements or media elements and the mill. In principle, a particle could remain in the mill for a substantial period of time without being subject to stress, while other particles may