Figure 11.1 Chocolate with "foot" due to incorrect viscosity. Reproduced from Beckett (2008).

single point measurements or by combining these using mathematical models to produce flow parameters, such as the yield value and plastic viscosity. The Casson model used to be the most frequently used within the confectionery industry and this will be explained, together with some of its limitations, in Section 11.3. The development of unified measurement protocols and ways of reporting flow properties of chocolate have been recommended by Servais *et al.* (2004). In addition a more advanced model was developed by Windhab (see Section 11.3).

Single point measurement systems do exist and these will be described, together with their limitations, in Section 11.4.

Rotational viscometers have become the industry standard and these are described in Section 11.5. However, the chocolate viscosity is altered by how it is treated and also by how the measurement is carried out (see Section 11.8).

The chocolate viscosity can be incorrect for a variety of reasons and it is important to determine the actual cause of a quality failure, so that it can be corrected. Section 11.9 reviews the factors that affect the flow properties of chocolate.

11.2 Non-Newtonian flow

Chocolate is a composite material of solid particles within a fat matrix, composed largely of cocoa butter, which will melt when the temperature is increased to around body temperature. Liquid chocolate is in fact a suspension. Without the solid particles being present, the liquid cocoa butter would have a single viscosity at whatever flow rate it was measured, that is it is Newtonian. Figure 11.2 shows two surfaces of area A separated by a gap of h where the lower plate is resting and the upper plate moves at velocity v as a result of pulling this plate at force F.

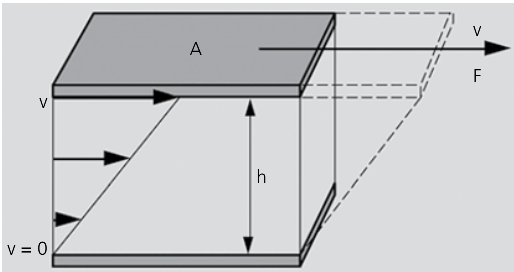

Figure 11.2 Two-plane model illustrating shear deformation. v = Velocity, A = surface area of plane, F = force and h = distance between planes. *Source*: Mezger (2006). Reproduced with permission of Vincentz Network.

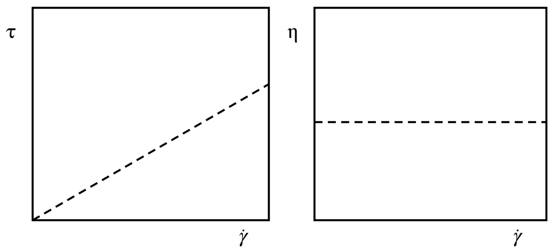

Figure 11.3 Shear stress – shear rate and apparent viscosity – shear rate relationship for Newtonian fluids.

A liquid confined between the two planes will deform as indicated by a linear velocity profile. The velocity gradient across the gap will be v/h and represents the rate at which the liquid is being sheared. This ratio is known as the shear rate, represented by $\dot{\gamma}$, and its SI unit is the reciprocal second (s^{-1}).

The ratio F/A represents the shear stress τ and its SI unit is the pascal (Pa). The force or shear stress required to move the upper plate to impart a desired shear rate is related to the resistance to deformation of the liquid, or the viscosity η:

$$\eta = \tau / \dot{\gamma} \qquad (11.1)$$

At any particular shear rate the value of η is known as the apparent viscosity and is normally measured in pascal seconds (Pa.s). For cocoa butter the force that is applied relates directly to the rate at which it moves, so the apparent viscosity is the same at all shear rates (Figure 11.3). This case is referred to as Newtonian behaviour.

In chocolate this is more complex due to the presence of a high proportion of solid particles. This is illustrated schematically for two flow rates in Figure 11.4. At rest or at zero shear the particles are randomly arranged forming a network preventing flow. The continuous phase of cocoa butter is trapped within this network. The apparent viscosity is relatively high. With the onset of flow upon increasing shear, particles will start moving in flow direction and elongated particles align in flow direction. The trapped liquid is liberated and layer formation as indicated in Figure 11.4 is likely to occur. This structure provides less resistance to flow and with increasing shear rate lower viscosities are measured until