2.1. INTRODUCTION

The "processability" of a rubber mix depends on three main aspects of materials behavior:

1. The flow properties.
2. The thermal or heat-transfer properties.
3. The vulcanization characteristics.

The extent to which the performance of rubber processing operations may be predicted, optimized, and controlled is dependent, in large measure, on the characterization and understanding of these properties. Before dealing in detail with individual properties and their measurement, it is important to review their influence on process behavior.

Rubber is a viscoelastic material and even in the unvulcanized state is capable of displaying behavior ranging from predominantly viscous to predominantly elastic, depending on temperature and rate of deformation. In processing, the main concern lies with flow and shaping operations, requiring that material temperatures and rates of deformation be adjusted so that the behavior is predominantly viscous. However, the time for which a conventional rubber mix may be held at an elevated temperature is limited by the onset of cross-linking, which effectively prohibits further flow and shaping operations.

Rubber processing can now be seen to be a compromise between conflicting requirements; raising the processing temperature generally results in the possibility of a higher output rate but brings with it the danger of the onset of cross-linking or scorch. Also, a temperature rise is usually an inevitable consequence of an increased output rate, arising from the conversion of mechanical energy to heat energy in the rubber (shear heating or viscous dissipation).

The temperature rise due to viscous dissipation is, as the name suggests, dependent on the viscosity of the rubber. More energy is needed to maintain
an equivalent flow rate with a high viscosity material than with one of low viscosity. However, increasing the temperature of a rubber reduces its viscosity, which indicates that there will be a trend toward a temperature – viscosity equilibrium in a flow process. Heat transfer to and from a process can therefore exert a considerable influence on its operating characteristics; and will depend on both the temperature – viscosity relationship of the rubber and the mode of heat transfer. The latter is determined by the flow patterns generated in the rubber. For simple laminar flow, or in the absence of flow, the primary mode of heat transfer is conduction; whereas in a process generating complex flow fields, physical movement of material to the metal surfaces of a machine at which heat transfer occurs results in far more effective heating or cooling. This mechanism is known as forced convection and is one of the primary reasons for the use of mixing screws in extruders.

Conductive heating results in pronounced temperature gradients due to the slow rate of heat transfer through rubber. This is particularly important for vulcanization, where the main aim is to heat the rubber as quickly and uniformly as possible to minimize the cure time. The selection of a suitable vulcanization process and optimization of the operating conditions first requires the measurement of the vulcanization characteristics and the heat-transfer properties of the rubber mix. Predictions of cure time and uniformity of cure can then be made using these measurements.

2.2. FLOW PROPERTIES OF RAW ELASTOMERS AND RUBBER MIXES

2.2.1. Viscous Flow

For the case of laminar flow between parallel plates, one of which has a velocity $V$ relative to the other plate (Figure 2.1), shear stress $\tau$ is defined as the force required to maintain the relative plate velocity $V$ divided by the

![Figure 2.1](image_url)