

5. Fibre Content

In order to specify any composite material, we must have a quantitative description of the proportions of the constituents it contains. In this chapter, we introduce the concepts of weight and volume fractions, and show how they relate to ply and laminate thickness.

5.1 Weight Fraction

In manufacture, it is natural to describe the constituents of a composite in terms of their proportions *by weight*. Constituents (reinforcement, matrix, fillers, etc) are routinely weighed before processing, and laminate weight per unit area may be a design specification.

The term *weight fraction* may be applied to any of the constituents. Hence, a manufacturer of GRP will invariably refer to the glass content as, for example, 25 wt%. A prepreg supplier will usually specify a resin content (eg 34 wt%).

In general, for a composite containing any number of different constituents:

$$\sum W_i = 1 \quad (5.1)$$

where W_i is the weight fraction of constituent i .

In a simple composite containing only fibre and matrix:

$$W_f + W_m = 1$$

$$\text{or} \quad W_m = 1 - W_f$$

5.2 Volume Fraction

For reasons which will become obvious, designers need the constituents to be quantified in terms of their *volume fraction*. Clearly:

$$\sum V_i = 1 \quad (5.2)$$

and for our simple fibre/matrix composite:

$$V_f + V_m = 1$$

$$\text{or} \quad V_m = 1 - V_f$$

In general, the weight fraction and volume fraction of a given constituent will be different, unless all the components happen to have the same density.

With a knowledge of the densities of the constituents, we can convert weight fraction to volume fraction and *vice versa*. For constituent a:

$$V_a = \frac{W_a / \rho_a}{\sum W_i / \rho_i} \quad (5.3)$$

and
$$W_a = \frac{V_a \rho_a}{\sum V_i \rho_i} \quad (5.4)$$

In a simple composite containing only fibre and matrix, we have:

$$V_f = \frac{W_f / \rho_f}{W_f / \rho_f + (1 - W_f) / \rho_a} \quad (5.5)$$

and
$$W_f = \frac{V_f \rho_f}{V_f \rho_f + (1 - V_f) \rho_a} \quad (5.6)$$

Equation (5.5) is plotted for three common polymer composites in Fig. 5.1. The assumed values of the densities of the constituents are given in Table 5.1.

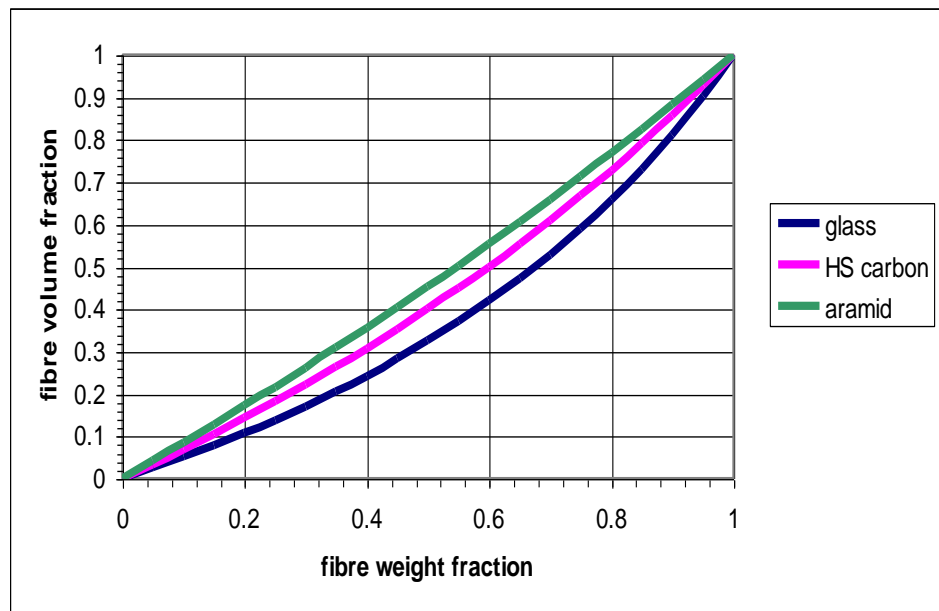


Fig. 5.1: Weight fraction / volume fraction conversion for common polymer composites.

Table 5.1: Typical constituent densities

material	density (kg/m ³)
E-glass fibre	2500
carbon fibre	1800
aramid fibre	1400
thermosetting resin (typical)	1200

5.3 Achievable Fibre Volume Fractions

The highest fibre volume fractions are obtained with unidirectional reinforcement. If we assume that all fibres have the same diameter, and can be arranged in a perfectly parallel fashion, then the theoretical maximum fibre volume fraction will be achieved with hexagonal close packing (Fig. 5.2).

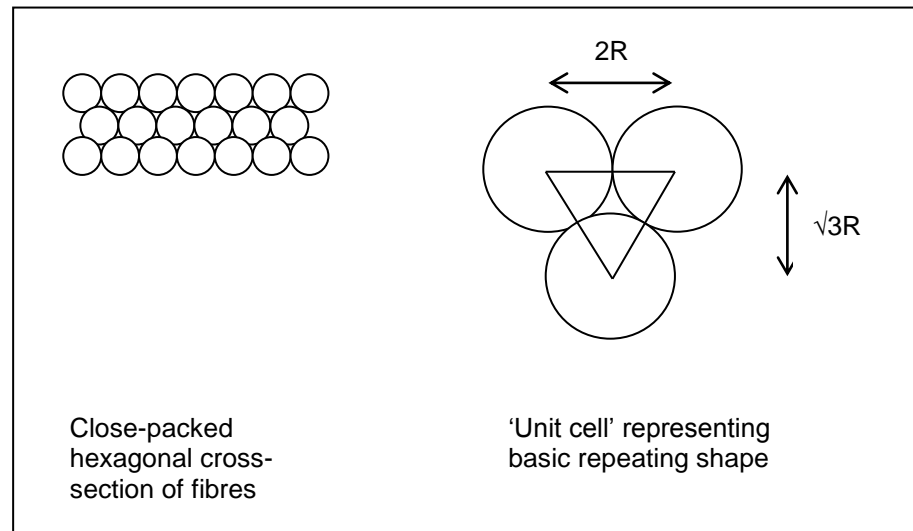


Fig. 5.2: Representation of close packing in cross-section of unidirectional fibre-reinforcement.

As the alignment of the fibres is fixed, the volume fraction is the same as the 'area fraction'. In the triangular unit cell in Fig. 5.2, the total area occupied by fibre is equal to three 60° segments. The unit cell has area $\sqrt{3} R^2$, so that

$$V_f^{\max} = \frac{3 \times \pi R^2 / 6}{\sqrt{3} R^2} = \frac{\pi}{2\sqrt{3}} = 0.907 \approx 91\% \quad (5.7)$$

Of course, such a high volume fraction is not achievable in practice – even if such a high degree of fibre collimation were available, the fact that fibres are touching would result in an ineffective composite. Of all the manufacturing process described in Chapter 4, filament winding is usually associated with the highest fibre volume fractions – with careful control of fibre tension and resin content, values of around 70% are possible.

As soon as the fibres are presented in non-unidirectional form, such as woven fabrics or random mats (see Chapter 3), a proportion of the reinforcement is oriented out of plane. Close packing is no longer possible, and the maximum fibre volume fraction is reduced.

Table 5.2 gives typical values for fibre volume fractions in polymer composites. Precise values will of course be process-dependent.

Table 5.2: Typical fibre volume fractions

reinforcement form	possible range of fibre volume fractions (%)	typical value for fibre volume fraction (%)
unidirectional	50 – 70	65
woven	35 – 55	45
random mat	10 – 30	20

5.4. Laminate Thickness

The thickness of a composite laminate depends on the amount of reinforcement and the relative amount of resin which has been included. For a given quantity of reinforcement, a laminate with a high fibre volume fraction will be thinner than one with a lower fibre volume fraction, since it will contain less resin.

Consider unit area of laminate, thickness d , containing n plies of reinforcement with areal weight A_w . The volume of fibre is given by nA_w / ρ_f . The total volume of the laminate is just d , giving the following equation for fibre volume fraction:

$$V_f = \frac{nA_w}{\rho_f d} \quad (5.8)$$

$$\text{or} \quad d = \frac{nA_w}{\rho_f V_f} \quad (5.9)$$

Equation 5.9 describes the situation when we know the fibre content and wish to calculate the laminate thickness, as in hand lay-up for example. Equation 5.8 would be used when the laminate thickness is fixed (as in RTM or compression moulding) and we want to calculate the fibre volume fraction.

By setting $n = 1$ in Equation 5.9, we can find the thickness associated with a single ply of given areal weight, moulded to different volume fractions. Figs. 5.3 and 5.4 show typical results for glass and carbon reinforcement.

Fig. 5.3: Single ply thickness vs. volume fraction – glass fibre.

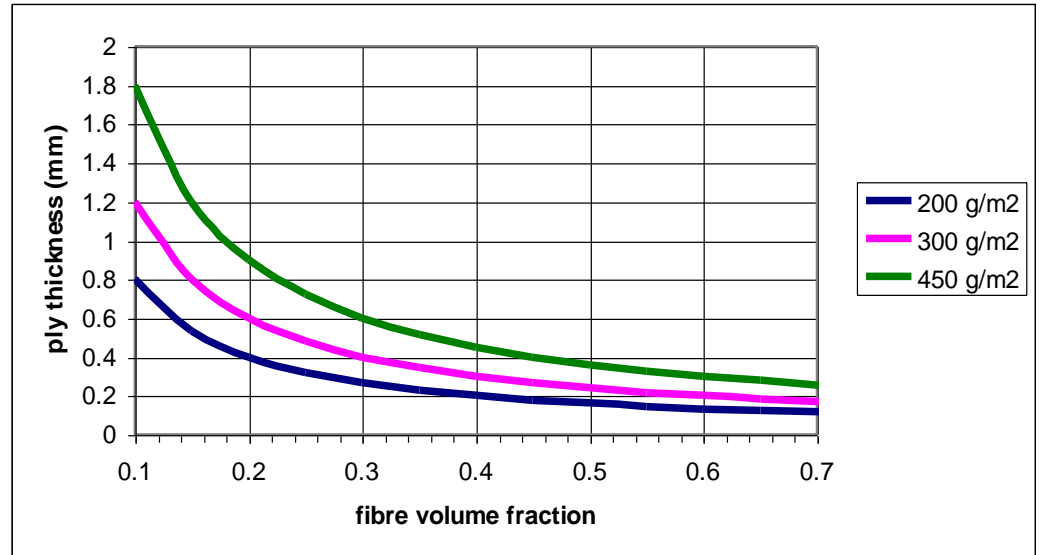
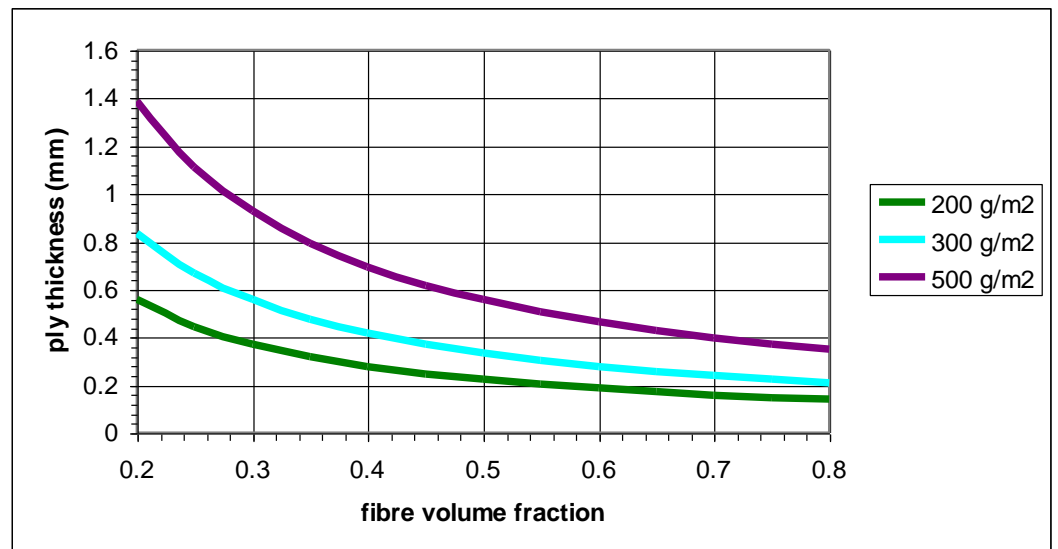


Fig. 5.4: Single ply thickness vs. volume fraction – carbon fibre.



5.5 Laminate Density

The density of a composite laminate is given by the simplest of the various ‘Rules of Mixtures’ – these are discussed in more detail in Chapter 6.

In general, a composite of total volume V containing constituents of different masses has a density given by

$$\rho = \frac{\sum M_i}{V} = \frac{M_1}{V} + \frac{M_2}{V} + \dots \quad (5.10)$$

Since mass = density \times volume, we can write Equation 5.10 in terms of the volume and density of each constituent:

$$\rho = \frac{\sum \rho_i V_i}{V} = \frac{\rho_1 V_1}{V} + \frac{\rho_2 V_2}{V} + \dots \quad (5.11)$$

But V_i / V is just the volume fraction of constituent i , so

$$\rho = \sum \rho_i V_i \quad (5.12)$$

where V_i is the volume fraction of constituent i .

For a simple composite comprising only matrix and reinforcement, we have

$$\rho = \rho_f V_f + \rho_m V_m = \rho_f V_f + \rho_m (1 - V_f) = (\rho_f - \rho_m) V_f + \rho_m \quad (5.13)$$

Composite density is plotted in Fig. 5.5 for glass, carbon and aramid reinforcements, using the same density data given previously.

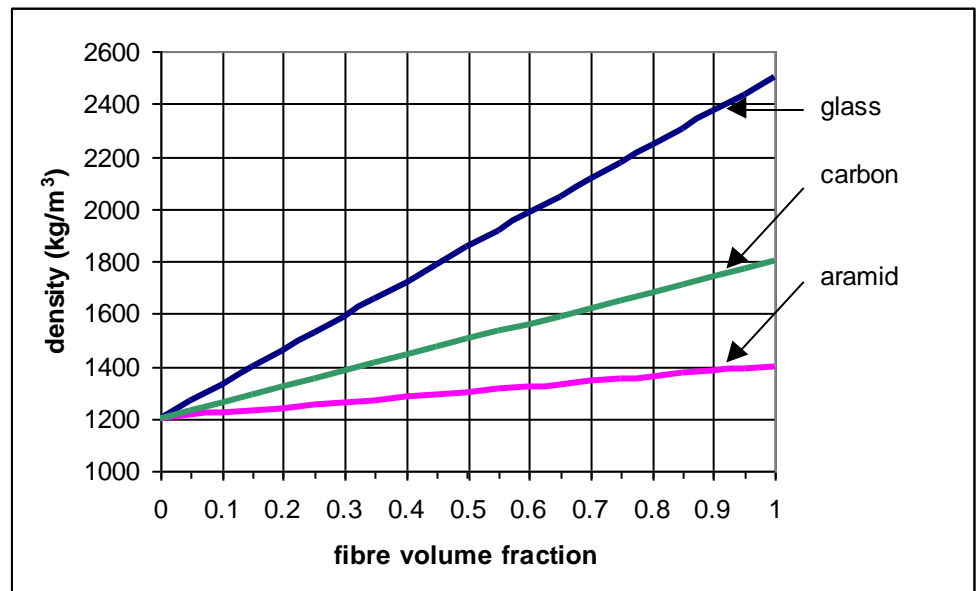


Fig. 5.5: Theoretical composite density vs. fibre volume fraction.

5.6 Compressibility of Reinforcement

In some processes, pressure is applied to aid laminate consolidation. Different reinforcement forms will react differently to applied pressure (P), and hence will contribute differently to overall laminate thickness.

Quinn (2002) reports data for a simple model of reinforcement compressibility, of the form

$$V_f = a + b\sqrt{P} \quad (5.14)$$

where a and b are empirical constants which depend on fibre type and weave style. Table 5.2 contains values of a and b for a range of different reinforcements, as reported by Quinn, and the resultant dependence of fibre volume fraction on applied pressure is shown in Fig. 5.6.

Table 5.2: Empirical constants for compressibility equation (5.10). Pressure is measured in bar.

fibre type	reinforcement form	a	b
E-glass	continuous filament mat	8.6	15.5
E-glass	chopped strand mat	20	14.7
E-glass	roving	32	24.0
E-glass	woven fabric	40	14.4
aramid	woven fabric	47	16.3
high strength carbon	UD fabric	34	25.6
high strength carbon	±45° fabric	35	16.3

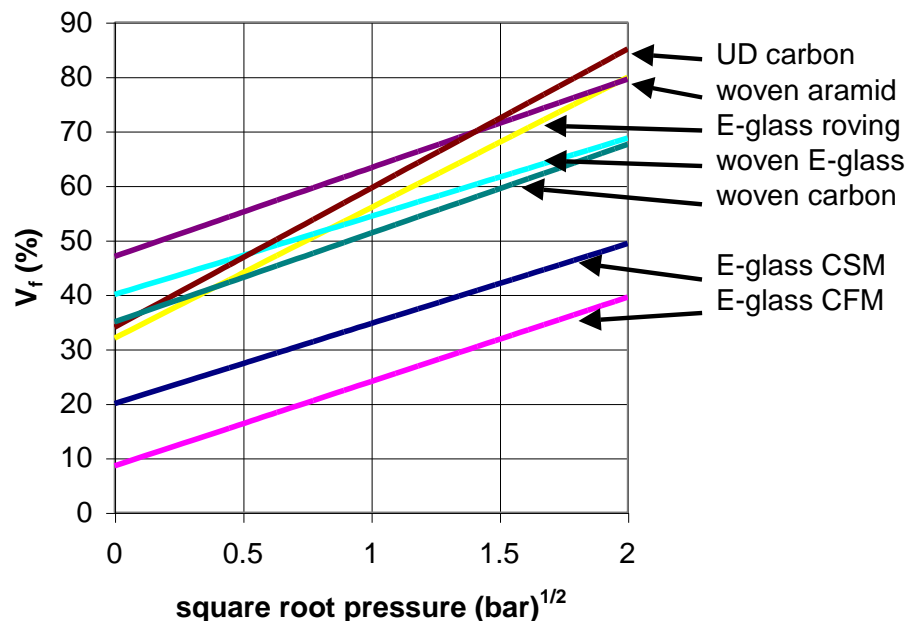


Fig. 5.6: Empirical compressibility of different reinforcements (Quinn, 2002).

5.7 Void Content

The presence of voids will add to the total volume, but not the weight of the composite. If V_v is the void content then Equation 5.13 becomes

$$\rho = \rho_f V_f + \rho_m (1 - V_f - V_v) \quad (5.15)$$

The decrease in composite density with void content is shown in Fig. 5.7 for glass/epoxy composites. If the fibre content is known and density can be measured with sufficient accuracy, then the void content can be estimated.

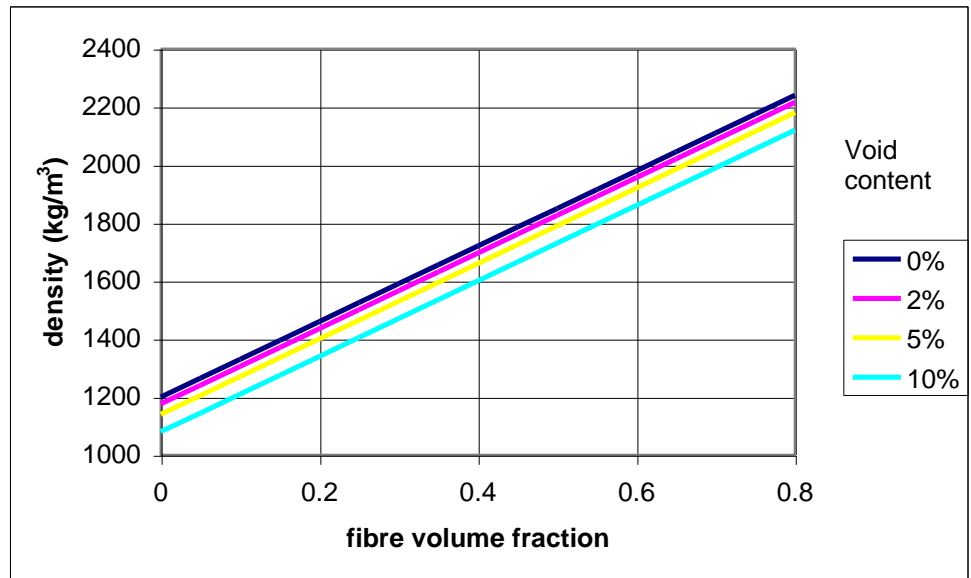


Fig. 5.7: Density of glass/resin composite at varying void content. Constituent densities from Table 5.1.

5.8 Exercises

1. What would be the maximum theoretical fibre volume fraction in a unidirectional composite if the fibres were arranged in a square array?
2. Calculate the fibre volume fraction in a cladding panel made from dough moulding compound (DMC) containing the following constituents:

glass fibre	22 wt%
polyester resin	53 wt%
calcium carbonate filler	25 wt%

Assume the density of calcium carbonate is 2700 kg/m^3 .

3. What will be the thickness of a laminate consisting of 2 layers of 450 g/m^2 chopped strand mat if a resin to glass ratio (by weight) of 2:1 is used?
4. What fibre volume fraction is achieved if 3 layers of 800 g/m^2 glass woven roving is compression moulded to a thickness of 2 mm?
5. What increase in pressure will be required to increase the fibre volume fraction of a woven carbon fabric from 55% to 60%?
6. We need to produce a laminate using woven glass fabric reinforcement with a thickness as close to 4 mm as possible. We have two fabric types available (300 g/m^2 and 500 g/m^2). Our manufacturing process is resin infusion, which produces laminates with a volume fraction of 52%. If we use 2 plies of the lighter fabric at the tool surface, how many plies of the heavier fabric are required? What will be the weight per square metre of the resulting laminate?