relative humidity is maintained below 65 per cent to prevent growths of staining fungi and bacteria.

4.4 Glass[21]

4.4.1 Nature of materials

4.4.1.1 Glass[22]

Silica (SiO_2) is the basic 'former' of glass but whereas in quartz and flint it is in a strictly symmetrical crystalline arrangement, here it is randomly arranged in a three-dimensional network. When molten material is cooled down too quickly for a strict arrangement of atoms to align themselves as it sets, a random network forms instead. This gives the resulting glass some fluid-like properties and an imprecise melting point. The melting point of pure silica glass is about 1700°C but if other elements, modifiers, are introduced into the glass, this point falls to less than 1000°C. Monovalent basic oxides (R_2O) such as soda (Na_2O) or potash (K_2O) modifiers behave as *fluxes* by interrupting some of the silicon–oxygen bonds and so breaking the continuous network. The unattached oxygen atoms become negatively charged and loosely hold the monovalent cations in the spaces of the network (figure 4.4):

$$-\mathrm{Si}-\mathrm{O}-\mathrm{Si}- \xrightarrow{R_2O} -\mathrm{Si}-\mathrm{O}^- \quad \mathrm{O}^- -\mathrm{Si}- \quad (R^+ \text{ ions})$$

This bonding is weak and the cations can migrate out of the network in the presence of water, making these glasses water soluble. To overcome this a second type of modifier, *stabilizers*, divalent oxides (RO) such as lime (CaO) or magnesia (MgO), must also be added. Being doubly

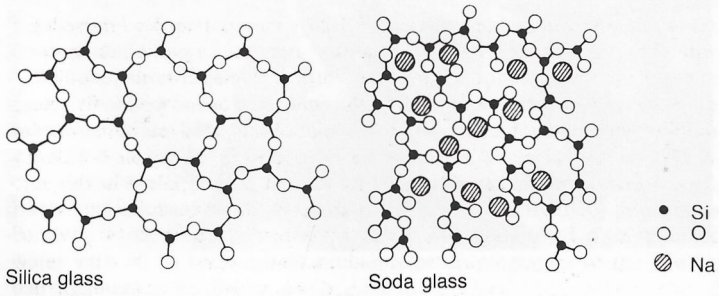

Figure 4.4 The arrangement of elements in glasses

charged they are more tightly held than the monovalent ions and so hold the fluxes within the network.

The content and balance of silica:flux:stabilizer (SiO_2:R_2O:RO) in a glass is critical in determining its melting point and character. An average soda–lime glass of 73% SiO_2:22% R_2O:5% RO has a melting point of about 725°C whilst a similar potash glass will harden at a higher temperature and more quickly. The former is more lustrous than the latter, whilst the substitution of some of the silica by lead gives lead crystal which, being soft, is easily cut to show great brilliance. Lead is also used to make the fusible glass required for the manufacture of enamels (section 5.1.2.6).

Colour in glass is usually given by transition metal ions held in the network like the modifying ions. The final hue[23] depends on the redox condition in the glass, the mixtures of ions present, and very precise concentrations of ions; thus it may be dangerous to speculate on the ions responsible for a particular colour. Colour may be extinguished by additives. Thus the blue-green hue of reduced iron is diminished by the introduction of pink manganese ions; the iron is oxidized to a yellow colour which, when viewed with pink from excess manganese, appears colourless. Some metal compounds can opacify glass but it may also appear opaque from large quantities of gas bubbles.

Glass for artefacts may be manufactured in one place and shaped in another. This latter activity is enormously varied, from the chipping and grinding of solid blocks of glass, to the bending of softened glass requiring temperatures of only 500°C, to the blowing of molten glass which requires much more heat (about 1000°C). Each technique of shaping leaves its own clues both in the overall shape of the object, its chemical composition (some glass being more suitable for cutting and some for blowing, etc.), and small visible traces such as bubbles and tool marks.

4.4.1.2 Associated materials

As is discussed elsewhere (section 5.1.2.6) metals may be enamelled[24] with glass which softens below the melting point of the metal, which flows to cover the metal, which adheres to it, and which has a similar coefficient of expansion to the metal; heavily leaded glasses often fit these requirements. Glass may also be inlaid into plaster in a technique known as *opus sectile*. Glass objects may be decorated by firing on powdered glass, metallic lustres or gilding, or by unfired paint applied in lacquer, varnish, or oil. Gold can be applied in the gold sandwich technique, when a design in gold leaf is sealed onto a glass object by a second thin layer of glass. Window glass is painted by enamelling, firing on a mixture of powdered glass and iron oxide, or stained yellow with silver by firing with silver sulphide. Window glass may be found in association with its cames,