4. CHEMICAL AND PHYSICAL INFORMATION

4.1 CHEMICAL IDENTITY

Synthetic vitreous fibers are inorganic substances, largely composed of aluminum and calcium silicates that are derived from rock, clay, slag, or glass (IARC 1988, 2002). While naturally occurring mineral fibers such as asbestos are crystalline in structure, synthetic vitreous fibers are amorphous materials. There are several methods of categorizing synthetic vitreous fibers based either on origin, chemical structure, morphology, application, or method of manufacturing. The most recent classification scheme proposed by the International Agency for Research on Cancer (IARC) has divided these compounds into two broad classes: filaments and wools. The filaments contain continuous glass filaments, while the wools contain glass wool, rock (stone) wool, slag wool, refractory ceramic fibers, and other newly engineered biosoluble fibers (IARC 2002). Glass wools are further subdivided into insulation wools and special purpose wools (see Figure 2-1). Continuous filament products are produced by drawing or spinning the molten mix from nozzles, while the wools are manufactured with a rotary or centrifugal process without using a nozzle (see Chapter 5 for details). Generally, the wool fibers tend to be shorter and finer than the continuous filament fibers, and their diameters may be more variable (IARC 1988). The typical chemical composition of these types of synthetic vitreous fibers is represented in Table 4-1. Special purpose glass fibers are sometimes used in high technology industries and have very specific properties that are tailored to their specific use. Although the procedures used to make these fibers are similar to those of glass wool, the operating parameters are usually adjusted to create products with extremely small diameters. One example of a special purpose glass fiber is included in Table 4-1.

Fibrous glass products are derived from powdered sand and largely consist of silicon and aluminum oxides. The final properties of the glass are dictated by the percent composition of other oxides including alkali metal oxides, alkaline earth oxides, and metal oxides like ZrO_2 and Fe_2O_3. Glass, like other insulating materials, provides a high resistance to the passage of electricity. Electrical glass (E-glass) is a continuous filament type of fibrous glass developed for electrical applications that has excellent heat and water resistance (IARC 1988, 2002). The high resistivity of E-glass is related to its low alkali oxide content. The majority of continuous filament fibrous glass produced is E-glass (IARC 1988, 2002). Other types of glass are used for certain types of specialized purposes, and relatively small changes in the

Table 4-1. Chemical Identity of Some Types of Synthetic Vitreous Fibers[a,b]

Percent composition	E-Glass	S-Glass	AR-Glass	Glass wool	Rock wool from basalt melted in a furnace	Rock wool from basalt and other material melted in a cupola	Slag wool melted in a cupola	RCF kaolin	RCF zirconia	Special purpose glass fiber 475 formulation[c]
SiO_2	52–56	65	60.7	55–70	45–48	41–53	38–52	49.5–53.5	47.5–50	57–58
Al_2O_3	12–16	25		0–7	12–13.5	6–14	5–15	43.5–47	35–36	5–6
B_2O_3	5–10			3–12						10–11
K_2O	0–2		2	0–2.5	0.8–2	0.5–2	0.3–2	<0.01	<0.01	2–3
Na_2O	0–2			13–18	2.5–3.3	1.1–3.5	0–1	0.5	<0.3	10–11
MgO	0–5	10		0–5	8–10	6–16	4–14	<0.1	0.01	0–0.5
CaO	16–25			5–13	10–12	10–25	20–43	<0.1	<0.05	2–3
TiO_2	0–1.5			0–0.5	2.5–3	0.9–3.5	0.3–1	2	0.04	0–0.1
Fe_2O_3	0–0.8			0.1–0.5				1	<0.05	0–0.1
FeO					11–12	3–8	0–2			
Li_2O			1.3	0–0.5						
SO_3				0–0.5						
S					0–0.2	0–0.2	0–2			
F_2	0–1			0–1.5						
BaO				0–3						5
ZrO_2			21.5					0.1	15–17	
P_2O_5							0–0.5			
Cr_2O_3								<0.03	<0.01	
ZnO										4

[a]Navy Environmental Health Center 1997; TIMA 1993
[b]As is standard practice, the chemical composition of the elements are reported as oxides, even though no such individual crystals exist in the fibers.
[c]There are several formulations applicable to this category and formulation 475 is generally representative.

AR-glass = alkali resistant glass; E-glass = electrical glass (so called because the low alkali oxide content makes it useful for electrical applications); RCF = refractory ceramic fiber; S-glass = high tensile strength glass (stronger than E-glass) chemical composition of the glass can result in significant changes to its optical, electrical, chemical, and mechanical properties. Chemical glass (C-glass) is highly resistant to attack by chemicals such as hydrofluoric acid, concentrated phosphoric acid (when hot), and superheated water. The chemical resistance is determined by the relative amounts of the acidic oxides (SiO_2, B_2O_3), basic oxides (CaO, MgO, Na_2O, K_2O), and amphoteric oxides (Al_2O_3). High-strength glass (S-glass) is almost completely composed of aluminum, silicon, and magnesium oxides and finds use in sophisticated high technology applications where high tensile strength is required; its tensile strength is typically 30–40% greater than E-glass. Alkali resistant glass (AR-glass) contains a high percentage of zirconium oxide, which makes this type of glass highly resistant to acidic and alkaline compounds.

The term mineral wool is often used to collectively refer to rock wool and slag wool, although occasionally, glass wool was included in this category. Similar to other glass fibers, the chemical composition of rock wool and slag wool are primarily aluminum and silicon oxides. However, these wools possess a higher alkaline earth oxide content (MgO and CaO) and lower alkali metal oxide content (Na_2O and K_2O) than glass wool. Rock wool is derived from igneous rocks such as diabase, basalt, or olivine, while slag wool is derived from blast furnace slag from the steel industry (Navy Environmental Health Center 1997).

Refractory ceramic fibers are a specialized type of synthetic vitreous fiber that are highly heat resistant and thus find use in high-temperature applications. Refractory ceramic fibers contain a much higher concentration of alumina than the other fibers listed in Table 4-1 and are sometimes referred to as aluminosilicate glasses. Although refractory ceramic fibers are amorphous at low temperatures, they undergo partial crystallization (devitrification) to quartz, cristobalite, or tridymite at elevated temperatures (Maxim et al. 1999b).

4.2 PHYSICAL AND CHEMICAL PROPERTIES

The important physical properties that are pertinent for organic compounds are generally not applicable to inorganic materials like fibrous glass. Properties such as vapor pressure, Henry's law constant, and octanol/water partition coefficient are exceedingly low and not measurable. Even properties like melting point are difficult to define since fibrous glass products are amorphous and do not experience a distinct melting point as crystalline materials do, but soften over a fairly broad temperature range. The term softening point is used for materials that do not possess a definite melting point and is often employed when discussing synthetic vitreous fibers. It represents the temperature at which plastic flow becomes viscous flow, and is specifically defined as the temperature at which the viscosity of the partial molten glass is $10^{7.6}$ poise (TIMA 1993). Since synthetic vitreous fibers are often used in textile products as a reinforcing material, the softening point is an important physical property. Some physical properties of the synthetic vitreous fibers listed in Table 4-1 are shown in Table 4-2. Since the final products within each class of fibers can be varied according to manufacturing specifications, the values listed in Table 4-2 should only be considered representative of the properties for each class in a very general sense.

Synthetic vitreous fibers are not actually soluble in water, but the term dissolution is often used to describe the durability of synthetic vitreous fibers, especially as it pertains to biological fluid. This should not be confused with solubility, which is the amount of material that dissolves in solution before it reaches chemical equilibrium. The dissolution rate is the rate at which a fiber reacts with a solution and is degraded in it. Under alkaline and acidic conditions, the silicate network of synthetic vitreous fibers can be attacked, resulting in the leaching of individual ions and the eventual disruption of the entire fiber network. Due to the larger surface area, fine fibers have greater dissolution rates than course fibers (see Section 3.4 for details).

Because the toxicity of fibers is related to their physical dimensions, it is important to characterize the size of synthetic vitreous fibers. In a typical glass fiber product, the average length is usually on the order of several centimeters, but the average diameter is usually on the order of a few microns. The nominal diameter is defined as the average fiber diameter in the finished product and varies according to fiber type, use, and manufacturing process involved (ACGIH 2001). The diameters of airborne fibers are an important physical property from a biological standpoint because thin fibers are considered respirable and may be deposited in the peripheral lung airways. Airborne fibers with diameters <3 μm are generally considered respirable in humans. There is also a strong correlation between the fiber diameter and the airborne fiber levels found in workplaces (Esmen and Erdal 1990; Esmen et al. 1979a, 1979b). Generally, the greater the fiber diameter, the lower the airborne fiber concentration. The nominal fiber diameter of continuous filament fibrous glass is usually in the range of 3–25 μm, depending upon the application, with typical diameters in the range of 6–15 μm (Navy Environmental Health Center 1997). The method of producing continuous filament fibers allows for excellent control of the preset fiber diameter and as a result, there is little variation in range of diameters for the resulting product. The production of rock wool, slag wool, and glass wool includes a rotary or centrifugal process resulting in nominal fiber

Table 4-2. Physical Properties of Some Types of Synthetic Vitreous Fibers[a]

Property	E-Glass	S-Glass	AR-Glass	Glass wool	Rock wool	Slag wool	Refractory ceramic fibers	Special purpose glass fiber 475 formulation[b]
Molecular weight	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Density (g/cm^3)	2.60–2.65	2.5	2.52	2.40–2.55	2.7–2.9	2.7–2.9	2.6–2.7	2.4
Softening point °C	835–860	970	680	650–700	No data	No data	1,740–1,800	650
Dielectric constant at 1 MHz	5.8–6.4[c]	4.9–5.3[c]	No data	No data	No data	No data	No data	No data
Modulus of elasticity (GPa)	70–75	85	70–75	55–62	55–62	48–76	76–100[d]	No data
Refractive index	1.55–1.57	1.52	1.525	1.51–1.54	1.6–1.8	1.6–1.8	1.55–1.57	1.53
Tensile strength (MPa)	3,400[c]	4,590[c]	3,700[c]	No data	482–689[d]	482–689[d]	1,000–1,300[c,e]	No data

[a]All data derived from TIMA 1993 unless otherwise noted.
[b]There are several formulations applicable to this category and formulation 475 is generally representative.
[c]Fitzer et al. 1988
[d]Navy Environmental Health Center 1997
[e]There are various commercial products of boron or silicon carbide filaments or yarns with high tensile strength, but these are crystalline fibers and technically not synthetic vitreous fibers.

N/A = not applicable

diameters in the range of about 3–7 μm for rock wool and slag wool and 3–15 μm for ordinary glass wool (Navy Environmental Health Center 1997). The smaller diameters of these fibers in comparison to continuous filament fibers, allows for the possibility that a small fraction of these fibers may be respirable when they become airborne. Special purpose glass fibers are produced by a flame attenuation process whereby the hot, molten glass is poured in front of a high temperature gas flame, resulting in fibers with a mean diameter of <3 μm and very often <1 μm. Refractory ceramic fibers (RCFs) are produced by melting and spinning or blowing of calcinated kaolin, aluminum silicates and metallic oxide blends, and high purity aluminum silicate. The typical fiber diameter of RCFs is 1–5 μm.

Christensen et al. (1993) employed light microscopy (LM) and scanning electron microscopy (SEM) to measure the length-weighted diameters of 22 synthetic vitreous fiber products obtained from 11 different manufacturers. In this study, nine different glass wool products, nine rock wool or slag wool products, three refractory ceramics, and a single special purpose glass fiber were analyzed. The results of this study are summarized in Table 4-3.

The results of a recent comprehensive workplace monitoring study using transmission electron microscopy (TEM) was reported by Mast et al. (2000), which characterized the airborne fiber dimensions of refractory ceramic fibers. Measurements of 3,357 fibers obtained at 98 workplaces yielded an airborne diameter range of 0.067–4.0 μm. The arithmetic mean and standard deviation were reported as 1.05 μm and 0.64 μm, respectively, while the geometric mean and standard deviation were reported as 0.84 μm and 2.05 (the geometric standard deviation is unitless), respectively (Mast et al. 2000). Fiber lengths ranged from 0.6 to 138 μm, with an arithmetic mean length and standard deviation of 20.6 μm and 19.3 μm, respectively. The geometric mean length and geometric standard deviation were reported as 14.1 μm and 2.48, respectively. The size distributions of airborne synthetic vitreous fibers at different locations under a variety of occupational settings were summarized in the most recent IARC monograph (IARC 2002) and these data are condensed in Table 4-4.

Table 4-3. Measured Diameters of Glass Wool, Rock Wool, Slag Wool, Refractory Ceramic Fibers, and a Special Purpose Glass Fiber[a]

Number of products studied	Arithmetic mean diameter range (μm) LM	Geometric mean diameter range (μm) LM	Arithmetic mean diameter range (μm) SEM	Geometric mean diameter range (μm) SEM
Glass wool				
9	2.4–8.1	1.7–6.6	1.2–7.7	0.8–6.3
Special purpose glass fiber[b]				
1	Not applicable[b]	Not applicable[b]	0.6	0.4
Mineral wool				
9	2.5–4.7	1.7–3.3	2.4–5.3	1.7–4.0
Refractory ceramic fibers				
3	2.3–3.9	1.5–2.8	2.4–3.8	1.7–2.8

[a]Data obtained from Christensen et al. (1993); for all samples, between 400 and 490 individual fibers were measured in order to derive the statistical quantities presented in the table.
[b]A single special purpose glass wool fiber was studied with a diameter too small to be accurately measured by LM.

LM = light microscopy; SEM = scanning electron microscopy

Table 4-4. Statistical Analysis of Airborne Fibers Under Different Occupational Settings[a]

SVF product or setting	GM diameter (µm)	GSD diameter	GM length (µm)	GSD length	Length-diameter correlation
Rock wool production	0.3–0.5	1.9–2.7	7.0–9.0	2.2–3.0	0.4–0.6
Rock wool use	1.2	2.7	22	4.0	0.7
Glass wool use	0.75	2.8	16	3.5	0.7
Glass wool use	0.8–1.9	1.4–1.9	9.5–30	1.4–2.5	0.2–0.7
Rock wool use	1.6–1.9	1.6–1.9	19	1.7–2.7	0.4–0.6
Glass wool house prefabrication	0.91–1.2	1.7–1.8	9.2–9.3	2.3–2.5	No data
Rock wool house prefabrication	1.3–1.7	1.9	12–17	2.5–2.8	No data
Installation of SVF batts	0.9–1.3	2.2	22–37	2.8–2.9	0.5–0.6
Installation of loose SVF with binder	1.0–2.0	1.8–2.2	30–50	2.3–2.6	0.4–0.6
Installation of loose SVF without binder	0.60	1.9	14–15	2.4–2.6	0.5–0.6
RCF production and use	0.84	2.05	14.1	2.5	0.4
RCF factory	0.96–1.2	1.7–1.9	12–19	2.4–2.6	No data
RCF factory	0.86	1.9–2.0	11–13	2.4–2.6	No data

[a]IARC 2002

GM = geometric mean; GSD = geometric standard deviation; RCF = refractory ceramic fiber; SVF = synthetic vitreous fiber