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A REVIEW OF ASBESTOS SUBSTITUTE MATERIALS IN INDUSTRIAL APPLICATIONS

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Summary

Asbestos is a fibrous material which makes a great contribution to human safety through its use in (among other things), fire protection materials and car brake linings. But it can also constitute a major health hazard to those who are exposed to the fine air-borne fibres.

This paper examines the properties and applications of asbestos, including those which lead to its being a health hazard. Over 1000 applications exist and only the more important of these are considered.

Some comments are made relating to the possible health hazards arising from some substitute materials.

1. Occurrence and varieties of asbestos

About 9/10ths of the earth's crust is made of silicates of which about 25% are in crystalline form. These include 30 different crystalline silicate materials occurring in fibrous form, collectively known as asbestos, of which only five have any commercial importance.

The annual global consumption of asbestos is about 4.5 million tons (1975). The three forms of asbestos significant in the UK market are:

Chrysotile (white)

This is the most commonly found asbestos mineral and accounts for about 96% of total annual production. It is characterised by relatively long, flexible fibres, and resistance to degradation by alkaline attack. Principal sources of chrysotile are Canada and the U.S.S.R., although little fibre is imported into the UK from the latter.

Amosite (grey-brown)

This has superior heat resistance to chrysotile and its principal use in the UK is for the manufacture of insulating boards. The fibres have a harsh, brittle acicular texture.

Crocidolite (blue)

This fibre has a variable texture, between flexible and brittle, depending on source. This mineral has greater fibre strength and is more resistant to acid attack than both the above types, and can be used in conjunc tion with chrysotile in the manufacture of asbestos-cement products. Its importation into the UK has been effectively banned on health grounds since 1970. A few imported products may however, be made from crocidolite (blue asbestos) and it can be found in insulation and spray form in buildings constructed before stringent restrictions were imposed upon its use in 1970.

Amosite and crocidolite are both members of the group of asbestos fibres known as amphiboles, and their principal source is Southern Africa. The other two commercial forms of asbestos, the amphiboles anthophyllite and tremolite, are little used in the UK. Anthophyllite is used in the USA in cement and plastics products.

2. Health hazards associated with asbestos

Medical evidence has shown that four diseases can develop following exposure to asbestos dust:

Asbestosis — formation of scar tissue on the lung which often leads to premature death, one of the pneumoconiosis group of diseases caused by mineral dust inhalation.

Mesothelioma — a relatively rare form of cancer of the outer surface of the lung or intestinal lining, which is fatal.

Lung cancer — increased susceptibility amongst those affected by asbestosis, particularly amongst those who smoke heavily.

Asbestos corns — usually trivial, cured by removal of splinter from skin. No carcinogenic correlation reported.

Whilst crocidolite is thought to be more dangerous, all types of asbestos can constitute a health hazard, but there may be a delay of up to 50 years before the effects appear.

The following points are important:

(1) Current medical evidence suggests that the risk is greatest with crocidolite, less with amosite and apparently less with chrysotile.

(2) It is not known what the maximum safe exposure to asbestos may be: levels are set under the 1969 Asbestos Regulations and based on a report by the British Occupational Hygiene Society (BOHS) although it may be that any level of exposure carries some risk.

(3) Mesothelioma can develop following relatively short periods of exposure. Asbestosis is mainly associated with long-term heavy occupational exposure.

(4) The risk of lung cancer among smokers exposed to asbestos can be up to 14 times that of an exposed non-smoker, and is at least 50 times as great as for a non-smoker in a normal environment.

(5) About 200 mesotheliomas are diagnosed per year in the UK of which at most, 60 occur in people with no known exposure to asbestos. Even if it is assumed that all of these cases are due to environmental exposure to low levels of asbestos, the risk is small. For example, it is less than 1/100th the chance of dying in a road accident.

Risks to the general public

Risks to the general public are dealt with in detail in Ref. 1.

3. Properties of asbestos

The numerous applications of asbestos are a consequence of its desirable physical and chemical properties, combined with a low material cost. It is this unique combination that makes the replacement of asbestos very difficult in many applications.

3.1 *Thermal properties*

The most widely known property of asbestos is its heat and fire resistance, although this resistance does not go as far as is popularly believed. Asbestos cannot be classed as refractory, although normally its properties are sufficient to withstand superheated steam and other elevated temperature industrial environments. Degradation of the crystal structure of asbestos and major loss of strength occur at temperatures in the range 300°—500°C. However, useful performance can be obtained at higher temperatures than this; specified working temperatures for some asbestos products may be as high as 600°C. The reasons for this are unclear, but some points of significance are apparent.

Chrysotile contains 14% by weight of hydroxyl (OH) groups, which is lost from its structure at temperatures greater than 450°C. The latent heat of vaporisation of this water content is thought to be a potent heat sink, protecting the remaining undegraded fibre. Further, the solid decomposition products are inert and of low thermal conductivity, providing additional protection to the remaining fibres, and maintaining structural integrity. It has been shown that, in some cases, asbestos can maintain its integrity at temperatures up to 1700°C.

3.2 *Other properties*

Various other properties make asbestos a valuable material. For instance, its resistance to chemical and biological attack is valuable in applications involving hostile environments, and in achieving a useful service life.

The friction and wear characteristics of chrysotile and its thermal decomposition product forsterite, a non-fibrous silicate, make chrysotile a widely used material in such applications as friction clutches, brake linings and bearings.

The high aspect ratio of asbestos fibres makes them useful as a mechanical reinforcement in both polymer and cement-base products.

3.3 *Price and availability*

This favourable combination of properties in one material, which is obtainable at a price significantly lower than its competitors in specific applications, makes asbestos an extremely attractive material. However, since asbestos is a limited natural resource, with an estimated resource life of about 25 years, prices are likely to increase, and alternative materials will have to be found on availability and cost as well as on health grounds.

4. Applications

4.1 *Construction industry*

More than half of the total production of asbestos is used for the manufacture of asbestos-cement sheets, pipes and moulded goods, and for insulation and fire protective building boards.

4.1.1 *Asbestos-cement products*

The primary function of the asbestos in asbestos-cement products is to act as a reinforcing fibre. The properties that make it useful in this role are high fibre strength and modulus and a large aspect ratio (ratio of length to diameter). This latter parameter is one of the factors that determines the reinforcement efficiency of fibres in composite systems.

These materials consist of a mix of Portland cement, water and asbestos (predominantly chrysotile) fibres, which are manufactured into the end products from the slurry by a process similar to that used in paper making. The asbestos fibres confer good drainage properties to the material, permitting the use of this type of manufacturing process. A degree of fibre alignment is achieved during the process, aligning fibres in the hoop direction in pipes and along the sheet length. Fibre content is usually about 15%.

4.1.2 *Asbestos-cement pipes*

These are commonly used for water supply, sewage and drainage applications, and in particular for the transport of some corrosive fluids. Asbestos-cement pipes tend to be favoured economically in the middle range of diameters, extruded plastics and metals being favoured for small bores, and conventional concrete for very large sizes of pipe.

The pipes have a laminar structure, such that any internal or external corrosive attack has only a very gradual effect, and this structure enables holes to be cut for branch pipes with little risk of cracking beyond the cut area.

The asbestos fibres perform a vital strengthening function in enabling the pipes to withstand tensile stresses as a result of internal pressure, e.g. in water mains. For this reasons, crocidolite, with its superior tensile strength to chrysotile, was widely used in the UK for pressure pipe construction prior to the stringent restrictions on its import.

4.1.3 *Asbestos-cement sheet*

Products of this nature are widely used for the roofing and cladding of large buildings, such as factories, for roofing in the familiar form of corrugated sheet, and in the form of moulded components for integrated roofing and cladding systems.

The fibre content confers useful increases in strength, stiffness and toughness on the material, but it is still fairly brittle and is not usually employed for primary load-bearing applications. One of the significant features of the fibre addition to the cement is that it enables the production of sheets with sufficient wet strength to permit moulding into complex shapes before the material dries.

The main attraction of asbestos cement sheet products is their durability and resistance to weathering attack, their non-combustibility and cost effectiveness usually being of secondary importance.

Substitutes for asbestos-cement products

Cladding panels are frequently manufactured from glass-reinforced thermosetting plastic (GRP) although these materials do not possess the fire resistance of asbestos cement and their combustion can lead to the evolution of toxic fumes.

Various thermoplastics, usually of the acrylic variety, have been used as cladding panels, in applications where their high transparency made their use desirable. However, several recent fires in buildings using these panels have resulted in the complete loss of the building due to the spread of surface flame on the panels, (e.g. the "Summerland" fire), and their use must be approached with caution.

PVC is often used in corrugated form, sometimes wire-reinforced, as roofing, in a similar manner to asbestos cement. It is generally used in applications where light transmission is desired, and should be of a UV-stabilised, flame-retardant grade.

Metals, notably aluminium, are also widely used in this application. GRP or GRP-wound concrete pipes are often suitable for use in corrosive environments and the traditional cast iron sewage pipe performs satisfactorily.

Rigid PVC and high-density polyethylene can be used for various pipework applications of asbestos cement.

Most of these materials are more expensive than asbestos-cement products, although certain thermoplastics may be cost-competitive in specific applications.

Glass-reinforced cement

In general, however, none of the above materials can be fairly considered to be a universal replacement for asbestos cement and the most promising route to achieve this objective at present is the development of glass-reinforced cement technology. Conventional E-glass fibre (which is commonly used in glass-reinforced plastics) cannot be used in conjunction with cement since the severely alkaline conditions produced during the setting of conventional Portland cement degrade the fibres and the resultant composite material rapidly loses its favourable mechanical properties. However, within the last ten years a high-zirconia, alkali-resistant glass fibre has been developed at the Building Research Establishment, Garston, England. This fibre is marketed by Pilkington Brothers Ltd., of St. Helens, England, under the name "Cem-FIL" for cement reinforcement purposes. Glass-reinforced cement usually contains between 3% and 7% of fibres, and typically one would expect a material containing 5% of fibres to have a modulus of rupture similar to that which would be expected from asbestos cement containing 15% of fibres (about 35 MN/m^2). Additionally, the glass-reinforced cement is considerably more impact resistant than asbestos cement of comparable strength. The "green" boards have wet strength and can be molded, and large bore pressure pipes can be produced. The final products perform adequately in preventing fire penetration. However, several drawbacks exist in the use of this material.

(1) The fibre is approximately four times as expensive (£1200—1500/ton) as the asbestos used in cement-based products and this, coupled with the less favourable economics of the production process results in a price for glass-reinforced cement some 70% greater than asbestos cement even allowing for the smaller fibre content.

(2) The drainage characteristics of a cement-water-glass fibre mix are poor and do not permit the manufacturing process for asbestos cement to be used in an unmodified form. The manufacture of glass-reinforced cement is relatively costly and requires a high capital investment.

However, the manufacturers of glass-reinforced cement are expending considerable effort on attempts to make the material on minimally-modified asbestos-cement plants. The impetus for this effort was the result of Japanese legislation about four years ago whereby asbestos was placed in the "dangerous chemical" category of materials. The research effort is presently concentrated on eliminating the asbestos content completely and this has been achieved by suitable plant modifications.

(3) Some attack on the glass fibre by the setting cement is necessary to achieve good fibre bonding and this requirement has raised doubts concerning the long-term durability of glass-reinforced cement. The product is too new for really long-term data to be available but manufacturers' findings for a seven-year period indicate that the strength of glass-reinforced cement when wet stored (the worst situation) drops to half its initial value in ap-

proximately two years, and then stays constant. Most existing uses of glass-reinforced cement have been restricted to non-load-bearing components (e.g. cladding) but the more demanding structural applications are gradually being attempted as knowledge of, and confidence in, the material grows.

4.1.4 *Insulating board*

Asbestos insulation boards are principally used on internal surfaces and partitions in buildings to provide both protection from spread of fire and acoustic insulation. Similar boards are used for parallel applications in marine construction, and to provide some measure of fire protection to the metal structural frame of the ship.

This product consists of asbestos in a calcium silicate (lime/silica) binder. The asbestos used is principally amosite, which provides a high degree of reinforcement at low board densities and has favourable drainage properties, and produces both board integrity and low shrinkage when subjected to fire. The boards are usually made by autoclaving.

Additionally, asbestos insulation boards are stable with a very low degree of moisture movement, are acid resistant, lightweight and easily worked. The relative merits of asbestos insulation board and other readily available building boards are shown.

4.1.5 *Asbestos replacements in insulation products*

(a) Mineral wool

Various types of mineral wool type fibres are available incorporated into insulation boards. Products incorporating mineral wool are usually cost-competitive with similar asbestos products, but their mechanical and insulation properties may be somewhat inferior.

(b) Vermiculite

Vermiculite is the name given to a group of hydrated laminar silicates resembling mica in appearance. On heating, vermiculite exfoliates, i.e. expands due to the (interlaminar) generation of steam from the water of constitution. Bulk material prices are low. The crude minerals cost about £40/ton, which rises to about £100/ton after they have gone through the exfoliation process.

The exfoliated granules may be delaminated to produce plates of vermiculite, and these have been used for the production of insulation boards. For example, one manufacturer uses a mix of delaminated vermiculite and alkali-resistant glass fibres in a lime-silica matrix. The vermiculite provides the insulation and fire protection properties, and the glass fibres maintain structural integrity. These boards meet the required specifications, but are generally inferior in performance to the comparable asbestos product, and cost about 30% more than the asbestos board.

(c) Ceramic fibres

Ceramic fibres, e.g. aluminosilicate, cannot be used for insulating boards owing to their tendency to dissolve in the lime-silica matrix during autoclaving.

4.2 *Asbestos textiles*

Chrysotile fibre forms the basic raw material for almost all the activities of the asbestos textile industry. The length and flexibility of the longer grades of chrysotile are such that spinning into yarn and cloth weaving are possible. Two basic types of yarn are produced: plain, possibly braced with an organic fibre; and reinforced, which incorporate either wire or another yarn such as nylon, cotton or polyester. The wire-reinforced yarns and textiles can retain their mechanical properties at temperatures up to 600°C. Recently developed textiles combined with resins and ceramic binders have successfully withstood short-term exposure to temperatures up to 2,200°C.

4.2.1 *Fire and heat protection clothing*

These are manufactured from asbestos cloth which is aluminised to give a heat reflecting surface. The metallic layer is bonded to the cloth by a thermosetting resin.

As an alternative, clothing made from temperature-resistant nylon fibre ("Nomex") has found application in fire-fighting, foundry work and as protective underclothing for racing-car drivers. The materials in suitable form can provide short-term protection from exposure to temperatures up to 1370°C and also for protection against molten metal impingement. Gloves made from this material are suitable for use with contact temperatures up to 300°C.

"Nomex" is suitable for protection against most chemical hazards, with the exception of some strong acids, and may be laundered with little deterioration in properties. "Nomex" is expensive relative to asbestos by a factor of about 3. However, the ability to launder "Nomex" clothing indicates that its useful life is much longer than asbestos clothing.

Clothing for heat protection is also made from special wool blends and has been tested for protection against splashes of molten steel at 1500°C. Aluminised grades are available for greater protection from radiant heat. The materials are resistant to chemical attack and may be laundered with no deterioration in properties. The wool fibres are surprisingly resistant to ignition and flame-spread and the clothing is competitive in price to asbestos-based products.

4.2.2 *Fire blankets, curtains and aprons*

In general the materials detailed above are also suitable for these applications. In certain circumstances blankets or rolls of mineral wool or ceramic fibres may be used, although these may tend to disintegrate more readily than the woven products.

4.2.3 *Ropes, yarns, tapes, etc.*

In general, satisfactory substitution of asbestos may be made with glass for many of the applications of these materials, provided that the softening of the glass at about 300°C is not significant. For higher-temperature applications, textile forms of the continuous ceramic and silica fibres may be suitable replacements if price permits.

The small number of minor textile applications for which no satisfactory alternative exists at present includes lamp and stove wicks, wipes for molten metal, diaphragms for some of the electrolytic cells currently employing asbestos, and some filter cloths.

4.3 *Thermal insulation and high-temperature applications*

For most high-temperature insulation applications chyrsotile fibre is the basic constituent because it combines the properties of resilience, strength as a reinforcement, flexibility, and heat resistance. In some cases amosite fibres are used, such as in the shaped block type lagging that can be applied to high-temperature pipes, in which a lime/silica binder is used.

However it should not be believed that the high-temperature properties of asbestos are in any way outstanding; major loss of strength occurs in the

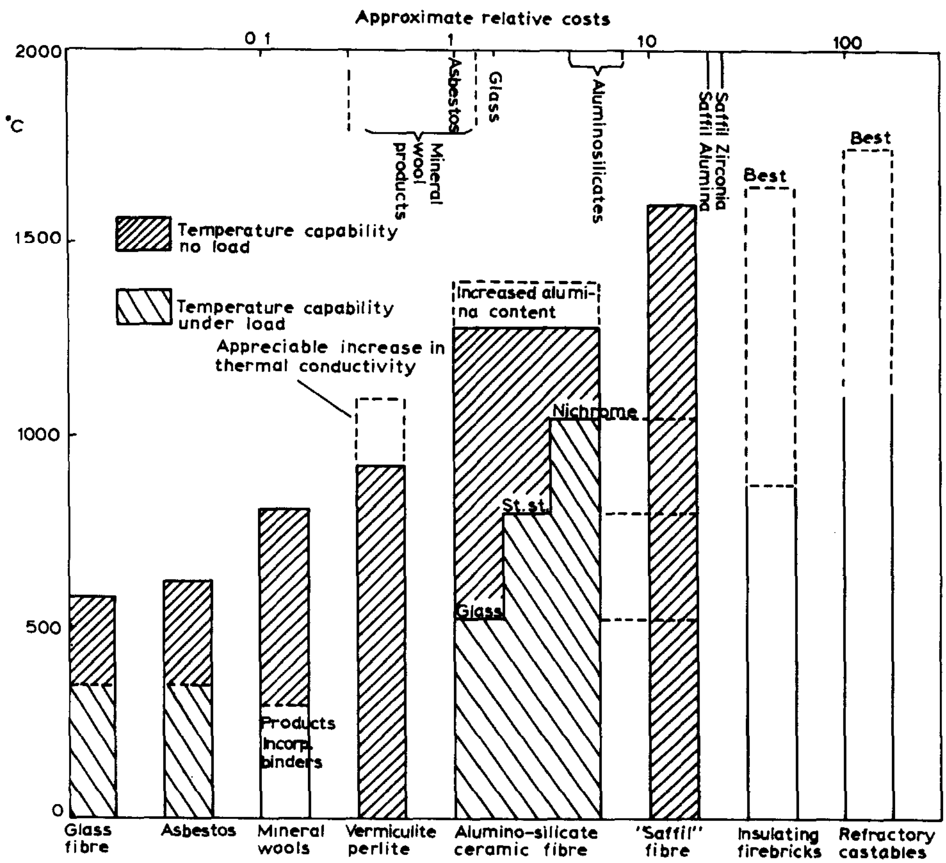

Fig. 1. High-temperature insulants.

region 300—500°C and it is rare that a continuous working temperature in excess of 600°C, even in unstressed situations, can be specified. Adequate substitutes are commercially available for thermal insulation purposes, most of which already find extensive application in higher-temperature regions where asbestos products cannot venture.

4.3.1 *Dry asbestos packings*

These are used mostly in conditions of dry heat, and are useful as flame spread barriers, e.g. in construction of prefabricated buildings, furnace and kiln door seals, and high-temperature caulking. Both unwoven and woven blanket materials are used as packings and laggings for thermal insulation, and also as heat and flame spread barriers, such as in heat shields in the engine compartment of vehicles, for which applications the asbestos may be aluminised for added protection.

4.3.2 *Asbestos jointings*

Asbestos in bulk fibre, woven or plaited form can be bonded with various elastomers such as rubbers and polychloroprene, which can be selected for resistance to specific oils and solvents. A high proportion of fibre is used and creates a high (or low) temperature resistant material in sheet form which has sufficient tensile strength to withstand pressure when used as gaskets. The ability to seal imperfections in metal flange faces by flow is also required, whilst maintaining clamping pressures to achieve leak-tight joints. Typical uses are in flange joints and boiler connections; pump, valve and pipe-joint seals in oil refinery and chemical plant; seals in internal combustion engines, ovens and autoclave doors; tank seals; and hydraulic systems.

4.3.3 *Gaskets*

These are a specialised form of jointing for use in internal combustion engines. The polymer/fibre mix is used because of its resilience, low cost, and resistance to the effects of hot gases, hot oils, and hot water/antifreeze mixtures. The familiar type of cylinder head gasket uses a sandwich construction of copper around asbestos paper or millboard, to cope with the severe working conditions of sealing high intermittent pressures combined with the previously mentioned requirements.

4.3.4 *Ceramic and mineral fibres*

Packed or sprayed asbestos is replaceable by many of the synthetic ceramic fibre product forms currently available, such as bulk fibre, strips, rope, spray, preformed shapes, felts, mats and blankets. Thermal stability is generally superior to asbestos and chemical stability is usually good. Asbestos has superior chemical stability in some situations, such as in hot, reducing atmospheres, and under hot, stressed conditions, but careful prediction of the service conditions usually allows a ceramic fibre to be selected that is adequate for the job. Although the cost of these materials is higher than asbestos this is frequently offset by increased service life, less maintenance, and increased process efficiency due to the ability to operate satisfactorily at higher process temperatures.

Cheaper mineral fibre products are available in many product forms. Products incorporating mineral wool are usually cost-competitive with similar asbestos products but their mechanical and insulation properties may be somewhat inferior.

Also various lime/silica and magnesia bonded products containing unspecified non-asbestos fibres (e.g. Paratemp) are widely available.

Ceramic fibre packings, mastics, die cut and preformed shapes are often suitable for sealing and gasket applications.

A considerably variety of ceramic fibres is available, the precise application deciding which will be necessary. In general, they all possess good thermal and chemical stability, low heat storage, resistance to thermal shock, low thermal conductivity and incombustibility. Ceramic fibre products are generally comparable to the corresponding asbestos products for thermal conductivity and, especially in blanket form, are being used increasingly for their acoustic properties, particularly at elevated temperatures where vibration is a problem. They are in widespread use as refractory insulation, seals, gaskets and fire-protective components in the broad spectrum of industry.

(a) Aluminosilicate fibres

These are available in a wide range of product forms and in two grades with continuous use temperatures of 1260°C and 1400°C (20% higher alumina content).

(b) Alumina and zirconia fibres ("Saffil")

Maximum use temperature rating for both is 1600°C. They are suitable for use in hot, reducing atmospheres as well as resisting general chemical attack. Zirconia has the greater resistance and the lower thermal conductivity and additionally is opaque to infra-red radiation.

Ceramic fibre textiles may contain insert materials to increase the fabric tensile strength. Alloy wire inserts are available for obtaining maximum tensile strength at elevated temperatures. Glass filament inserts are used in applications where metal is undesirable (e.g. dielectrics). The following insert materials are available:

Glass	service to 520°C
Stainless steel	service to 800°C
Nichrome wire	service to 1050°C

Where tensile strength is not important the materials may be used to their maximum service limit of 1260°C (or higher).

4.3.5 *Vermiculite and perlite*

Vermiculite for high-temperature insulation is normally bonded with a high-alumina cement or fireclay and is therefore competitive with ceramic fibres for hot-face lining applications. Many vermiculite products can withstand temperatures of 1100°C. Expanded Perlite is used as an insulating cover on the surface of molten metal to prevent excessive heat loss during pouring, to produce refractory blocks and bricks, and to top off ingots. The material is used occasionally to 1100°C although above 925°C the thermal conductivity increases appreciably.

4.3.6 *Solid ceramics*

Additionally certain specialised applications can use solid sintered ceramics, e.g. alumina and silicon nitride. These can be fabricated into components such as insulation washers and rotary pump seals, which would commonly be machined out of a high-density asbestos board of the "Sindanyo" type. Bulk raw materials costs can be low (e.g. alumina at about £300/ton), but the unconventional processing route and specialised manufacturing techniques necessary for solid ceramics may necessitate the purchase of finished components from a manufacturer, so that cost comparisons are not directly possible. However, it is probable that the cost of a solid ceramic replacement would be much higher than that of the asbestos component. This may to some extent be offset by superior properties, e.g. better wear resistance in rotary and sliding seals.

4.4 *Asbestos millboard*

This is one of the most versatile asbestos materials used in industry. Features of millboard that contribute to this versatility are: ease of cutting or punching to shape; useful thermal insulation properties; impregnability with bonding agents or cement; ability to be wet-moulded; and compressibility.

Typical uses are for the fabrication of rollers for transport of hot materials in the steel and glass industries, as formers for wire-wound electrical resistances, flange gaskets for joints in ducting and trunking used for high-volume/low-pressure gas transport, cylinder head gaskets, insulating linings to minimise heat losses from ovens and moulds, as plugs and stoppers for molten metal containers, and in resin-impregnated form for clutch facings.

4.4.1 *Substitutes*

For many applications, millboards made from aluminosilicate fibres can provide a direct replacement if the extra cost be acceptable. They are made by a suction method from an aqueous slurry of fibres, and are available in thicknesses up to 50 mm. They are also available with a high-temperature silica binder. These aluminosilicate fibre millboards have been successfully used for the process rollers in plate glass manufacture. For the insulation applications, if the thermal conditions are not so severe as to necessitate the use of ceramic fibres, one of the several types of mineral fibre block and slab products should be an effective substitution. Cobalt rollers for the steel heat-treatment application have been used as a millboard substitute, but are considerably more expensive than the asbestos product.

4.5 *Friction materials*

Asbestos-based brake and clutch linings and pads are in widespread use, particularly, but not exclusively, in the automotive industry. Drum brake linings are usually moulded from a mixture of short chrysotile fibres, phenolic resin, and various mixtures of fillers. Brake pads may be similarly made, or can use a woven asbestos cloth which may be reinforced with brass wire, impregnated with phenolic resin, as commonly used in clutches.

The chrysotile fibre performs a complex function in these applications which is not completely understood. The fibres stiffen and strengthen the filled phenolic resin matrix and can maintain these properties at the high temperatures generated during, for example, braking and clutch slipping. The friction and wear characteristics of the asbestos fibres and their decomposition product, forsterite, are thought to affect the braking efficiency and service life of the products. Forsterite is a non-fibrous silicate and is not thought to constitute a health hazard. Investigations have established that the dust produced from the wear of asbestos friction materials contains only 1% to 2% of asbestos fibres. Repeated exposure to this dust is a potential hazard to persons working in close proximity to these products (for example, garage mechanics) and it is strongly recommended that components should be cleaned with suitable vacuum extraction equipment, or a damp rag, rather than the more accustomed practice of blowing dust away with a compressed-air line.

4.5.1 *Substitutes for asbestos in friction materials*

(a) *Sintered products*

Sintered metal, ceramics and metallised bonded products have been available for many years. However, the high thermal conductivity of these materials creates a risk of brake fluid heating and boiling, which can cause erratic performance and inconsistent behaviour between cold and hot conditions.

(b) *Vermiculite*

Delaminated vermiculite is used in friction materials which are available commercially throughout Europe. The materials maintain their strength at high temperatures, and, since vermiculite is compatible with the commonly used phenolic resins for this application, little alteration in manufacturing methods is required. Other fibres are sometimes used with vermiculite and some developments are mixtures of asbestos and vermiculite, aimed at reducing the asbestos content.

(c) *Silicon nitride*

This material was used for the brake pads in the Concorde prototypes 001 and 002. It was found to have a longer service life than asbestos, and a higher thermal conductivity which in this application was desirable. The material is expensive, the powder costing about £5,000/ton, and the components were heavier than the carbon-reinforced carbon composites eventually adopted.

(d) *Carbon/carbon composites*

These materials are used for the brakes on the production Concordes, and have also been used on racing cars where they are more efficient than asbestos materials under the high service temperature conditions.

The anistropy of these materials produces uneven heat flow and thermal expansion coefficients, and additionally they have relatively low tensile and impact strengths. Furthermore, their high cost (a development price quoted is greater than £10,000/ton) justifies their application only in specialised circumstances.

(e) *Other fibres*

Various other fibres have been used in phenolic binders, such as steel, glass, mineral wool and aluminosilicates. They all have their drawbacks and none is yet as good as asbestos, especially for higher-temperature applications such as disc brake pads.

However, a considerable volume of work is currently in progress on the use of steel and glass fibres. Vehicle trials are underway, and it is estimated that asbestos substitute materials are available for about 30% of the friction products market, the exception being the heavier duty applications, such as disc-brake pads where high-temperature surface conditions are encountered.

The first use of steel fibres in friction materials was by Germany, prior to and during World War II, due to the difficulty in obtaining imports of asbestos. It was found that the brakes worked well, with little loss of efficiency when wet, but that the wear debris was abrasive and severely damaged the counterface. It has been found easier to use steel than glass in the manufacturing process, which uses the same volume fraction of steel as asbestos. The steel fibre is usually of the fine steel wool type and is about four times as expensive as the asbestos used in friction applications.

Glass-fibre base friction materials also produce a very abrasive wear debris with corresponding damage problems. At high temperatures, the glass can melt, which can produce a sudden undesirable loss of friction, since the sliding surfaces can be effectively lubricated by the molten glass.

Brakes using steel and glass fibres tend to be considerably noisier than their asbestos counterparts.

4.6 *Dry rubbing bearings*

One significant application for asbestos composite materials is for plain rolling bearings. In this application a matrix of thermosetting phenolic resin is used to impregnate asbestos cloth or yarn. The principal advantage of these materials is that, although they can be lubricated by oil or grease, and in some cases are supplied impregnated with up to 7% mineral oil, they are also able to function effectively without lubrication, or lubricated by in-situ process fluids or seawater.

The life of dry rolling bearings is comparable with that of lubricated bearings only at low sliding speeds, in practice, principally in oscillating applications. Their use is generally advantageous for applications having sliding speeds below 1 m/s and where the use of a lubricated bearing is impossible or unattractive due to:

(a) Inability of lubricants to survive in the operating environment due to factors such as high or low temperatures or high levels of ionizing radiation.

(b) Penalties of cost, complexity, size or weight associated with the provision of adequate lubricant feed, for example where bearings are inaccessible and cause relubrication and maintenance difficulties.

Typical applications of dry rubbing bearings include automotive steering column bushes brake and clutch pedal bushes, bearings for textile spinning frame spindles, food slicer bearings, copying machine rollers, bearings for conveyor rollers, aircraft control and undercarriage bearings, large railway bearings, dock equipment, lock gates.

Asbestos bearings in particular find extensive application for large marine bearings where high loads and low sliding speeds are encountered and seawater may be used as lubricant. Important examples are rudder and steering gear bearings and stern shaft bearings.

Historically, lignum vitae in the form of axial staves within a gunmetal bush was commonly used. This arrangement was also suitable for lubrication by seawater but the hard, oily wood suffered from a tendency to swell in water and the life expectancy was low when high loads were encountered. The next generation of marine bearings employed bronze or white-metal bearings, which are still in extensive use. Metallic bearings are suitable for a wide range of applications when cost is not of prime importance and constitute excellent bearings when loads are moderate and speeds sufficiently high to create a continuous lubricant film. However, under the high load, low speed regimes encountered in marine bearings, the consequent marginal (or "Boundary") lubrication can lead to excessive galling and seizure. The reinforced plastics bearing materials also have other major advantages in this application: white metal is inherently weak under shock loading conditions; in marine environments galvanic corrosion is likely to occur with metal bearings; plastic matrices are less stiff (lower Young's modulus in compression) than bearing metals, which means that misalignment is a less serious problem.

These advantages lead to a reduced maintenance time and longer life expectancy, which when combined with good machinability and ease of fitting all contribute to significant cost reduction in this application.

Asbestos bearings additionally are tolerant of line and spot loading. This good performance as a bearing material is not well understood, but it is suspected that the tendency of the flexible chrysotile fibres to "brush-out" on the bearing surface is significant.

4.6.1 *Substitutes for asbestos-reinforced thermosets in bearing applications*

Reinforced thermoset

Asbestos-composite bearings are a member of the reinforced thermoset family of plain bearing materials. Among the other members of this family which do not contain asbestos are:

(a) Polyester-bonded textile laminates with MoS_2 or graphite.

(b) Cellulose-fabric based phenolic laminates with uniformly distributed PTFE or graphite.

The members of the family have broadly similar physical and chemical properties. However, the maximum operating temperature of asbestos reinforced composites is generally higher — up to 175°C as against 100° to 130°C for the other composites, and the coefficient of linear expansion lower.

Other plain bearing materials

It is beyond the scope of this paper to discuss in detail a large variety of specific circumstances, but considering the high load, low speed, low wear rate and modest temperature category into which the majority of asbestos bearing applications fall, the potential substitutes are:

(a) Polyimides

(b) Woven and resin-bonded PTFE fibre

(c) Graphite impregnated metals

(d) PTFE impregnated metals

In marine applications the latter two, which are metal-based, would not be preferred for much the same reasons as white metal, and one is therefore left

TABLE 1

Competitive bearing materials

	Cost relative to asbestos
Polyimides	2.2— 6
Glass filled	
Solid lubricant filled (graphite/MoS_2)	
Woven and resin-bonded PTFE fibre	2.4—10
Metal-solid lubricants	5 — 6
Graphite-filled irons + MoS_2	
Graphite-filled bronzes + MoS_2	
Ag-PTFE	
PFTE impregnated metals	1.2— 2.5
Steel	
Porous bronze	

with a choice between polyimides, or woven and resin-bonded PTFE fibre, both of which carry a heavy cost penalty, in relation to asbestos composites. In applications where the environment and/or engineering conditions are not so demanding the impregnated metals would be an economic and technically satisfactory proposition, although in general many such applications could be adequately covered by oil-porous metal bearings.

4.7 *Electrical insulation*

Asbestos is widely used in the electrical industry in the form of paper, tape, cloth, and board. It is frequently applied as a felted material and as a filler for natural and synthetic insulating resins. In dielectric applications the most common impregnant is a solid resin. The impregnation of the asbestos by resin increases its dielectric strength, improves its mechanical properties and supplies a moisture-proofing material in order to offset the hygroscopic property of the asbestos itself. Laminates suitable for use to 180—200°C can also be made from felts or woven cloths with appropriate high-temperature resins. They are used for low-voltage transformers, armature slot wedges, furnace parts, domestic heating equipment and similar applications. Resin-bonded papers and boards use for example, phenol formaldehyde, polyvinyl acetal, epoxy or silicone resins according to the temperature of service and may also contain glass or other fibres. Asbestos papers and mat are made by methods similar to cellulose paper.

Most cases in which asbestos textiles and papers are employed for electrical insulation also demand a degree of thermal and/or chemical protection. Chrysotile asbestos and smaller amounts of amosite and tremolite are used by the electrical industry for insulation purposes as textiles. In this form asbestos is employed for the insulating of wires and cables, especially those which are designed for low-voltage, high-current use under severe temperature conditions; arcing barriers in switches and circuit breakers; and for braided sleevings for electrical appliances and insulated conductors where fire protection and resistance against mechanical abrasion is sought. Asbestos in the form of cloth tapes and sleeving may be reinforced with glass or natural fibres.

Asbestos-cement products are used in the electrical industry for the construction of mechanically strong and heat-resistant rods, tubes, cylinders and plates. Applications include panel boards, arcing barriers and insulating tubes and cylinders used in the construction of air-cooled transformers.

Cheap asbestos boards bonded with starch and calendarised are not very strong but will withstand fairly high temperatures. Asbestos millboard is used for applications such as formers for wire-wound electrical resistances.

For electrical use the choice of asbestos free from iron and the removal of any iron oxide or metallic particles is important. Asbestos materials are not suitable for high-voltage insulation, nor for high-frequency insulation because of their high dielectric loss even when dry. Their main electrical use is in low-voltage high-temperature situations and for confinement of arcs.

4.7.1 *Substitute electrical insulants at high temperatures*

Chrysotile fibres deteriorate noticeably at 450°C but suffer some loss of strength at 300°C; prolonged heating in air at temperatures even below 200°C will ultimately produce loss of strength. Although these fibres are more resistant to temperatures above 200°C. Consequently, in applications such as insulation sleeving for cables and battery separators direct replacement with glass fabrics is usually satisfactory.

Glass fabrics of all kinds (cloth, tape, tubes, cords) are woven from yarn and used in resin-bonded laminates. Glass chopped strand mat is also used for moulded or hand-load composites. The fibres do not alter in mechanical properties up to 200°C and their strength is roughly halved at 350°C; they are not suited to applications where severe flexing is involved.

Glass fibres served onto wire and treated with suitable resins are used in high-temperature windings. This type of insulation is more vulnerable to abrasion than most other wire coverings.

Polyimide and polyethersulphone are examples of high temperature polymeric materials which are used as wire and cable coatings suitable to 200°C and 260°C respectively where ability to withstand high temperatures combined with toughness and flexibility justifies the cost. The latter has the additional advantage of withstanding soldering temperatures for short periods.

For cable and wire insulation up to 530°C ceramic fibre cloth, tape or sleeving may be used with glass filament inserts to maintain high temperature strength.

4.8. Asbestos composites

In this application, the high aspect ratio of asbestos fibres is significant in producing an effective reinforcement of the polymer matrix, enhancing such properties as strength, stiffness and toughness.

Excluding such composite products that are dealt with in other sections (e.g. floor tiles, bearings, friction materials) still leaves a wide range of asbestos/polymer composites in use across the whole engineering spectrum. They are usually made with a thermoset matrix, although composites using the thermoplastic matrices such as nylon and PVC are also in fairly widespread use.

Typical applications are for small machine parts, usually made by an injection moulding method, such as vehicle distributor caps, fans, fan shrouds, small casings and other similar products. In these applications, the fibres are effectively randomly aligned in three dimensions.

One widespread application for an asbestos/thermoplastic composite is for junction, destination and mileage signs used on roads and motorways. These are manufactured from asbestos in a PVC matrix, and consist essentially of a random array of asbestos fibres in two dimensions.

Composites using asbestos in various degrees of alignment have been made, such as those based on "Durestos" and "Pyrotex" materials, and using woven cloths of asbestos, which utilize the asbestos in an efficient manner and enable a significant proportion of the ultimate properties of the fibres to be achieved in practice. However, these materials use the more expensive, longer fibre length grades of chrysotile, and an expensive alignment process, so that it is often simpler and cheaper to use continuous glass or other fibre for this type of high performance composite application.

4.8.1 Substitutions for asbestos in composites

In general, glass fibre provides an adequate replacement for asbestos in many of the injection moulded component applications. Longer fibre lengths are necessary in glass than with asbestos to achieve comparable aspect ratios, and this necessitates careful manufacturing control to avoid fibre damage during component fabrication. Glass fibres are of lower modulus than asbestos. Consequently, if component stiffness is important, the volume loading necessary with glass fibres may be higher than with asbestos fibres. A wide range of glass-fibre filled injection-moulding, sheet-moulding and dough-moulding compounds are readily available, and a suitable asbestos alternative may often be found immediately.

5. Health hazards with fibrous materials other than asbestos

If it is required to replace asbestos on health grounds, then it is sensible to ascertain whether or not the suggested replacement itself constitutes a health hazard.

For all practical purposes, the risk from fibrous materials is limited to inhalation of the fibres. Recent research on asbestosis has suggested that the fibrosis is caused principally by fibres between about 5 μm and 100 μm long. Longer fibres than this settle out in the environment and are not inhaled, or are deposited by interception in the narrow upper airways and seldom reach the finest bronchioles in the lungs. The falling speed of fibres is governed by the fibre diameter rather than length, and this produces a further size separation in the respiratory passages. Fibres greater than 2 μm in diameter (which also tend to be the longest) are mostly deposited in the upper respiratory tract, or are eliminated in the sputum. The definitions of fibre size in the Asbestos Regulations, 1969, Appendix, Technical Data Note 13, is based on these observations of causative fibre sizes for asbestosis, and probably also for bronchial cancers.

For the mesotheliomas, less information is available. What evidence exists suggests that the biologically active fibres are straight, up to about 1 μm in diameter. Some of the recent data suggests that fibre size and shape are more important than chemical composition in producing carcinogenic effects. A consequence of this is that exposure to airborne fibre dust of any type with diameter less than 0.5 μm and several μm long is potentially hazardous.

With these observations in mind, examination of fibre diameter data suggests that the various synthetic refractory type fibrous materials that can be used to substitute for asbestos in elevated temperature applications may themselves constitute a health hazard. A mean fibre diameter in the range 2—3 μm is quoted for all these fibres, suggesting that a significant proportion of them have diameters less than the 2 μm level thought to be significant in the contraction of asbestosis. It is also possible that a small proportion of the fibres are of diameters less than 0.5 μm, the suggested causative size for mesothelioma to be a potential hazard. The as-manufactured length of these fibres is much longer than the suggested hazardous lengths, but of course, as with asbestos, manufacturing and handling processes can create fibre fragments that may disperse as airborne dust. These fibres are all comparatively new products, all being available in the UK for less than ten years, and since the induction period for asbestosis may be anywhere in the range 15 to 40 years, one cannot state with certainty that refractory ceramic fibres do not consitute a health hazard. However, a thirty year study in the USA has shown no health problem with workers in aluminosilicate fibre manufacture, and an investigation into "Triton" has indicated no mesothelioma potential, and a minimal tendency towards lung fibrosis.

It would appear that the fibre diameters of glass and carbon, which are reproducible with a very small spread of diameters, constitute no health hazard of the pneumoconiosis or bronchial cancer type. Fibres in glass-wool materials as supplied for insulation purposes average 5 to 6 μm in diameter (as also do some more recent types of glass fibre intended for reinforcement purposes) and so far industry surveys have shown no pattern of a related disease except for a higher incidence of bronchitis among retired workers.

TABLE 2

Physical characteristics of fibrous materials

FIBRE PROPERTY	Chrysotile Asbestos	Crocidolite Asbestos	E-Glass	A-S Carbon (Grafil)	Suffil Alumina (ICI)	Suffil Zirconia (ICI)	Triton (Morganite)	McKechnie T.I.	Fiberfrax (Carborundum)
Diameter / μm	Fibril 0·02 Fibre 0·03-100	~ 0·5	10–12	9	Mean 3	Mean 3	Mean 2·8	1–10 Mean 2·5	Mean 2–3
Length /mm	Fibril 0·25-5 Fibre 1–80	< 5	Chopped or continuous	Chopped 1, 3 and 6 continuous	N.A.	N.A.	Mean 100 up to 250	25–200	40–250
Chemical Constitution	Hydrated Magnesium Silicate	Hydrated Sodium-Iron Silicate	Calcium Alumino-Silicate	Graphite	Alumina	Zirconia	Alumino-Silicate	Alumino-Silicate	Alumino-Silicate

Research in the U.S.A. has shown a carcinogenic effect by surgically implanting glass fibres of less than 1.5 μm diameter and longer than 8 μm into the chest walls of rats. However, the greater than 30 year history of industrial use of glass fibre, with no carcinogenic relation apparent, suggests that this artificial situation does not represent the situation with the more commonly used sizes of glass fibre.

Glass fibres have been found in some cases to be more irritant to the skin than asbestos, occasionally making their handling during manufacturing processes somewhat unpleasant.

A limited amount of data is also available on some of the minerals suggested as asbestos replacements in various applications. Mineral wood fibres, with a diameter of about 5 μm are unlikely, on the basis of the discussion of fibre sizes presented previously, to constitute a health hazard.

It has been shown by observation of miners that a pneumoconiosis disease is associated with the extraction of mica.

Studies have also been performed on vermiculite that suggest that it has no tendency towards carcinogenicity or the production of fibrosis in the lungs.

Expanded perlite can generate airborne dust. This has been examined as a possible health hazard, and is thought to cause no problem, except for nuisance. Experience in the USA going back nearly 30 years has indicated no related disease pattern with the use of perlite.

6. Legislation

Full details of the regulations applying to operations involving asbestos are contained in publications issued by the H.M. Factory Inspectorate, Department of Employment.

The present acceptable level of airborne asbestos fibres is set in the UK for chrysotile and amosite at 2 fibres/ml. The regulations relating to blue asbestos are more stringent the standard being set at 0.2 fibres/ml in the UK. In the USA no differentiation is made between the types of asbestos; the acceptable level has recently been set at 2 fibres/ml, although 0.5 fibres/ml has been suggested as a new standard.

Between the limits of 2 and 12 fibres/ml, exposure to levels higher than 2 may in certain cases be permitted at the discretion of the Factory Inspectorate. Fibres are defined as being of a length greater than 5 μm and having an aspect ratio (length/diameter ratio) of at least 3:1. There is no upper limit for the length of the fibres, but a maximum diameter of 3 μm is defined.

In addition, the Factory Inspectorate must be informed in writing 28 days before any building containing blue asbestos is demolished, or any process involving blue asbestos is undertaken.

Greatest concern at present exists over demolition and delagging work which may release large quantities of asbestos dust into the air, constituting a domestic health risk. It is not, in general however, believed that there is a serious danger to the general public from airborne asbestos dust.

Concern has also been expressed over the adequacy of the inspection system carried out by the Factory Inspectorate, and the severity of the penalties which may be imposed for not complying with the regulations. It has been suggested that a limit of 100 fibre-years/ml should be adopted as an exposure standard for use with asbestos. i.e. that exposure to a dust level of 2 fibres/ml is acceptable over a working lifetime of 50 years, or 5 fibres/ml for 20 years, to reduce the risk of contracting asbestosis to 1%.

7. Conclusions

(1) Two applications (cement-base products and fire-resistant insulation boards) account for more than half the asbestos consumed at present.

(2) Many applications can utilise existing fibre type products as an alternative, but

- (a) certain specialised applications cannot be met with existing alternative fibres;
- (b) it is not considered that the health hazards which may be encountered with fibres other than asbestos have been evaluated with any certainty.

(3) Not all applications can always satisfactorily employ an existing alternative material.

(4) Where an alternative can be found, there is usually a cost penalty involved and the properties of such an alternative are sometimes inferior to those of asbestos.

(5) Although the quantity of asbestos consumed can be reduced, it is unlikely that its use can be eliminated. Even if production of asbestos products were banned, a problem would still occur in handling in existing installations. There is consequently a need for education regarding the hazards and stringent enforcement of safety regulations.

(6) Certain areas have been identified as potentially the most difficult in which to find adequate replacements. These are:

- (a) Asbestos-cement building products.
- (b) Some insulation applications.
- (c) A few textile applications.
- (d) Specialised bearings.
- (e) Some jointings.

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