CHAPTER 2   LITERATURE REVIEW

2.1   AUTOMOBILE BRAKE LINING INDUSTRY AND ASBESTOS

Friction materials have been widely used in a great variety of plant and equipment throughout the world, it includes such applications as: industrial, marines, quarries, forklift, agricultural, elevators/lifts, automobile, etc.

As one of the most common type of friction material, brake lining device is designed to slow or to stop the movement of a mechanism or an automobile. The incorporation of brake lining in automobile is for our convenience and safety. According to the actual risk statistics for traffic accidents, brake linings are responsible for only about 1% of traffic accidents. The entire brake system including the brake lining accounts for the cause of about 2.4% of the traffic accidents (Anderson, 1995).

The Ontario Royal Commission on Asbestos (1984) has proved that "the use of asbestos-containing friction materials does not pose a detectable risk to the general population". According to Lynch (1968), only a very small proportion of the asbestos worn off from brake linings is released as free fiber. It might represent only 0.2 micrograms per day, according to Commins (1985).

Despite this, the safety and health issues are a growing concern with the use of asbestos as a major component in brake lining, particularly asbestos used in the manufacturing process. The waste generated posed high risk, both to the environment and human health.

2.1.1 History of Friction Materials

During the early machine age, friction materials for brake and clutches were natural fiber composites, such as wood and leather. About 90 years ago, an Englishman named Frood invented the first composite friction material. The friction material company he founded, Ferodo, made rapid advances using a combination of organic binder resins and chrysotile asbestos. These improved friction materials were needed as faster and heavier vehicles evolved. Many other brake lining manufacturers developed similar friction materials, some used chrysotile asbestos textile while others used millboard or molding compounds. Their binder resins were always organic, so they were called organic friction materials (Anderson, 1995).

Solid state sintered ferrous and copper-based friction materials were developed for some highly loaded and high temperature applications. These included disc brakes for aircraft and race cars, as well as some industrial brakes and clutches. In addition, fiber reinforced composition brake shoes have replaced nearly all of the cast iron railboard brake shoes on diesel powered trains (Baker, 1992; Anderson, 1995).

2.1.2 Asbestos

Asbestos is a generic term applied to a wide variety of naturally occurring mineral silicates that are separable into fibers (Hodgson, 1979; Manjunath and Cheremisinoff, 1992). It is mineralogically divided into 2 main families: (a) Serpentine and (b) Amphibole. Table 2.1 shows the major recognized species of asbestos which form these families.

Table 2.1 Major species in Serpentine and Amphibole family

Serpentine Family	Amphibole Family
Chrysotile (white asbestos)	Cummingtonite-Grunerite asbestos (amosite or brown asbestos) Crocidolite (Blue asbestos), Anthophyllite asbestos Tremolite asbestos Acetinolite asbestos

(Hodgson, 1979; Schreier, 1989; Manjunath & Cheremisinoff, 1992)

Characteristics and Commercial Use

Asbestos is described as cotton like fibrous minerals with length greater than 5 μm and a length to width ratio that is at least 3:1 (Delaine and Miosh, 1988; Schreier, 1989; Warren, 1979). It has been used for over 2000 years (PRO-ACT, 1996). Specific attributes and characteristics vary with different types of asbestos, but the commercially valuable asbestos minerals, in general, for fibers that are incombustible, possess high density strength, good thermal and electrical insulating properties, and moderate to good chemical resistance (Manjunath and Cheremisinoff, 1992). The above characteristics made asbestos appear well suited for an estimated 3,600 separate commercial and

industrial applications. These include roofing and flooring products, fireproofing textiles, friction products, reinforcing material in cement, pipes, sheets and coating materials, as well as thermal and acoustical insulation (Rajhans and Bragg, 1978; PRO-ACT, 1996). Only three types (chrysotile, amosite and crocidolite) have been of commercially importance until recently, with chrysotile now representing >98% of current use worldwide, and amphibole <2% (Dunning, 1995).

Chrysotile Asbestos

Chrysotile asbestos has been used widely as the main constituent and primary reinforcing fiber in the fabrication of friction materials due to its specific characteristic like high density strength, durability, flexibility and resistance to wear (Manjunath and Cheremisinoff, 1992). The asbestos-containing friction materials include brake lining materials in roll, strip or sheet form, brake blocks and liners, brake lining segments, disc brake pads, clutch facings, automobile transmission discs and band liners. It has been used in friction materials from less than 10% (by weight) in railroad brake shoes, to over 60% in some passenger car drum brake lining segments. Typical asbestos usage is between 30% - 65% (Hodgson, 1973; AIA Health and Safety Publication, 1985; Anderson, 1995).

Even though other friction materials have been developed and used, Chrysotile asbestos-based organic friction materials still dominate the market (Anderson, 1995). About 27,000 metric tons of Chrysotile asbestos is being consumed per year. In 1994, 9,500 metric tons was used in the manufacture of friction materials for both new vehicles and the aftermarket (Pigg, 1995).

Health Concerns

Many studies have proven that the fiber dimensions are considered to be highly significant, especially where the risk of the fiber entering the human lung is concerned. Asbestos with length < 10 μm can remain in the air for long periods of time and be easily inhaled into the lung alveoli. Once inhaled, their spear-like shape allows them to become embedded in lung tissues. On the other hand, large and heavy fibers tend to fall rapidly to the ground when released into the air (Warren, 1973).

Epidemiological studies have proved that the exposure to airborne asbestos fiber can cause diseases which disrupt the normal functioning of lungs, and it may take as long as 20 to 30 years before symptoms appear and/or could be detectable. Three specific diseases - asbestosis (a fibrous scarring of the lungs), mesothelioma (tumor of the mesothelial tissue lining the chest cavity adjacent to the lungs) and bronchogenic carcinoma (cancer originating with the air passages in the lungs) - have been linked to exposure of asbestos (Manjunath and Cheremisinoff, 1992).

2.1.3 Background and Recent Developments of Asbestos Regulations for Friction Materials in The United States of America

In US, the commercial use of asbestos began in the early 1900s and peaked in the period from World War II into 1970s. Consumption of asbestos was 795,000 tons annually in 1973, however it dropped drastically to 217,000 tons annually in 1983 (Manjunath and Cheremisinoff, 1992). This was because, in the mid 1970s, several types

of asbestos materials such as spray-applied insulation, fireproofing and acoustical surfacing materials were banned by United States Environmental Protection Agency (US EPA) due to the "asbestos hysteria".

The US EPA and Occupational Safety and Health Administration (OSHA) have major responsibility for regulatory control over exposure to asbestos. Emission of asbestos to the ambient air is controlled under the Section 112 of the Clean Air Act 1970, which specify control requirements for most asbestos emissions, including work practices to be followed to minimize the release of asbestos fibers during handling of asbestos waste materials (EPA, Asbestos/NESHAP, 1990).

EPA has been regulating many asbestos-containing materials which, by EPA definition, are materials with more than 1% asbestos. In 1989, EPA issued a final rule under Section 6 of the Toxic Substances Control Act (TSCA) to prohibit the future manufacture, importation, processing and distribution of asbestos in almost all products (PRO-ACT, 1996). The Asbestos Ban and Phaseout Rule (40 CFR 763.160) was scheduled to eliminate asbestos in most commercial products in three stages over a seven years period beginning in 1990 and ending in 1996 (PRO-ACT, 1996).

The EPA also engaged in a dialogue with Original Equipment Manufacturers (OEM) in September 1992 and requested that they terminated the use of asbestos in new vehicles by 1994. EPA sought a "voluntary agreement" with Chrysler, Ford and General Motor and foreign OEM on the above matter. However, the OEM did not agree to a formal voluntary phase out of asbestos friction products as about 20% of new cars and

formal voluntary phase out of asbestos friction products as about 20% of new cars and trucks were using asbestos-containing braking system. EPA's asbestos rule was challenged in US court and as a result of the court decision, most asbestos products are no longer subject to the ban and phaseout rule (Pigg, 1995; PRO-ACT, 1996).

While the use of asbestos brake in new vehicles has generally declined, a grand total of 4.1 million pieces of asbestos brakes were used in the years 1993, 1994 and 1995. With an average road life of 6 - 8 years, the aftermarket is expected to remain strong for several years in the future. In this regards, there is complete acceptance by EPA and OEM of the premise that vehicles initially designated to use asbestos brakes should have asbestos replacement brakes installed. General Motors promised to service asbestos-containing OEM parts with asbestos-containing replacement parts as long as vehicles equipped with these OEM parts remain in service (Pigg, 1995).

Additionally, EPA is working on a proposal called Significant New Use Rule (SNUR) since 1993. Such proposal would declare that replacement asbestos-containing friction products could not be marketed without first obtaining approval from EPA for vehicles originally equipped with non-asbestos brakes (Pigg, 1995).

Due to the stringent regulations and strict enforcement, trade union pressure, rising litigation cost and negative public perception, the automotive industry has started asbestos elimination plans. This has forced the friction material manufacturers and their suppliers to seriously investigate and develop replacement or alternative fibers.

2.1.4 Substitute for Asbestos

A good substitute for asbestos should possess the characteristics such as non-flammability, high strength, flexibility, reasonable cost and safety. With respect to safety, the substitutes must not induce disease in those exposed to them and also must not endanger lives in other ways by having inferior strength or durability, increased flammability, or other undesirable characteristics. For instance, the chance of increased automobile accidents due to a possible inferior substitute material must be weighted against the probability of anyone being harmed by the small amounts of chrysotile asbestos emitted from brake drums. Also, the health effects of emissions from the substitute brake lining materials must be considered (Baker, 1992; Lehr, 1992).

The requirements of strength and flexibility make it necessary that asbestos substitutes be fibrous. Generally, the thinner and longer the fibers, the stronger, more flexible and useful they are. There are several substitute fibers recommended by US EPA in 1988: aramid (e.g. Kevlar or Twaron), glass fibers, mineral wool (and other man-made glass fibers), steel wool, ceramic fiber, titanate fiber and wollastonite. However some of these are now considered to be toxic too (Anderson, 1995).

Unfortunately, none of the above fibrous materials, by itself, was an acceptable asbestos substitute for friction materials (Anderson, 1995). Consequently, many brake lining and clutch formulations use a combination of the asbestos fiber grades and other

fibrous materials to obtain the best combination of cost, processing and end product performance. The suitability of asbestos substitute depends on their temperature application range, as well as product design that minimizes the need for dry forming and machining operations (Burgess, 1995).

The processability and performance of the finished friction materials are highly dependent upon the combination of fiber types and the manufacturing process techniques used for particular friction material formulations. Little information is available about the combination effects of various fibers, precise composition and manufacturing process of brake lining and clutch facing, because they are held as closely guarded proprietary secrets (Anderson, 1995).

2.1.5 The Manufacturing Process of Brake Pads

The typical operations involved in the manufacture of vehicle brake friction pads are depicted in Figure 2.1. The process starts with the initial mixing of asbestos with other raw materials. The mixture is placed in molds and formed "cakes" in presses and initially cured. It is cut to shape and a final cure is achieved in an oven. The major source of wastes or residues are generated during the final finishing operation, (including grinding, drilling and counter-sinking) when the product is ground to desired dimension. It was reported that the highest asbestos concentration has been noted in cutting and drilling operations where 14.4 fibers/ml was generated, while the concentration mixing and preparation at the front end of the process generated 11.0 fibers/ml (Burgess, 1995).
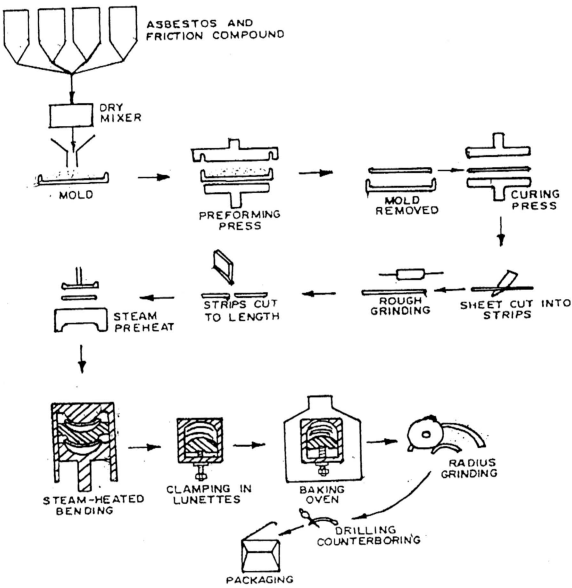
Figure 2.1 General flow diagram of the manufacture of the automobile brake pads.
(Sluis-Cremer, 1975)

2.2   WASTE MINIMIZATION

2.2.1 Definition of Industrial Waste

The United Kingdom Environmental Protection Agency (UK EPA) 1990, (Section 75) provides a formal definition of wastes:

(a) any substance which constitutes a scrap material or an effluent, or other unwanted surplus substance arising from the application of a process; and

(b) any substance or article which requires to be disposed of as being broken, worn out, contaminated or otherwise spoiled.

Besides the regulatory and formal definition, according to Smith (1997), waste can be simply characterized as "material or energy which, in the eye of the producer, arises at a rate and in a form such that it has no value". Goodrich (1994) also defined waste as the material purchased that is not consumed by customers, and it is used for activities which do not add value to the service rendered to the customers.

Thus, waste materials include:

- raw materials left in drums or sacks
- accidental spillage and associated cleaning materials
- fugitive emission/evaporation
- gaseous discharges
- contaminated materials
- off-specification products and
- obsolete or redundant stocks of raw materials, intermediate or final products

2.2.2 Costs Associated with Wastes

Goodrich (1994) has described the various consequences of waste generated which is related to material and energy cost, product quality, machinery capacity and environmental compliance. Clark (1995) has further elaborated the various aspects associated with waste generation by using a inter-related web, as illustrated in Figure 2.2. Obviously, some aspects go far beyond pure monetary consideration. It extends over the activities and future viability of an industry.

Any costs incurred due to the wastes produced during the production process - excess raw material costs, administration costs associated with transportation, storage and disposal costs, must be considered as part of the production costs. In addition, the consequences of unnecessary third-party liability costs and the costs related to remedying improperly disposed hazardous materials, unnecessary depletion of natural resources, generation of poor customer relationship and causing negative public image, lead to the ultimate inevitable loss of business to those more efficient producers who have taken all such factors into account (Clark, 1995).

2.2.3   Benefits of Waste Minimization

Although the implementation of waste minimization project may require some additional investment in the initial stage, it can provide long-term benefits in various aspects as demonstrated in the Figure 2.3.
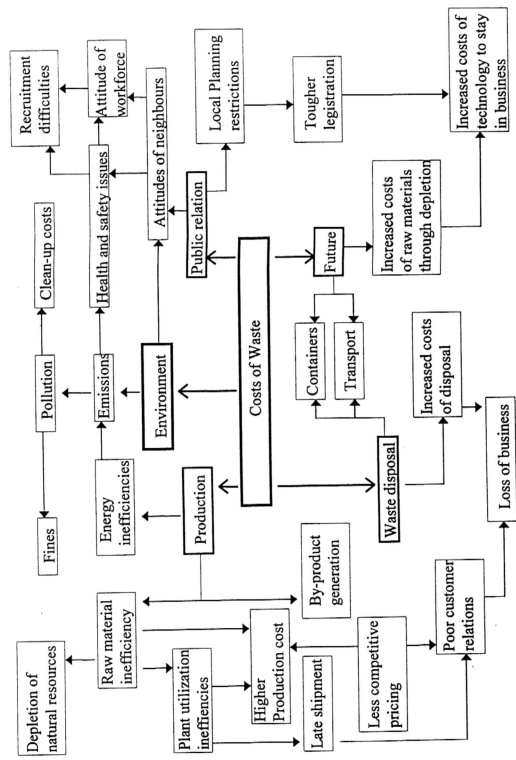
Figure 2.2   Various aspects of costs incurred from waste generation (Clark, 1995)
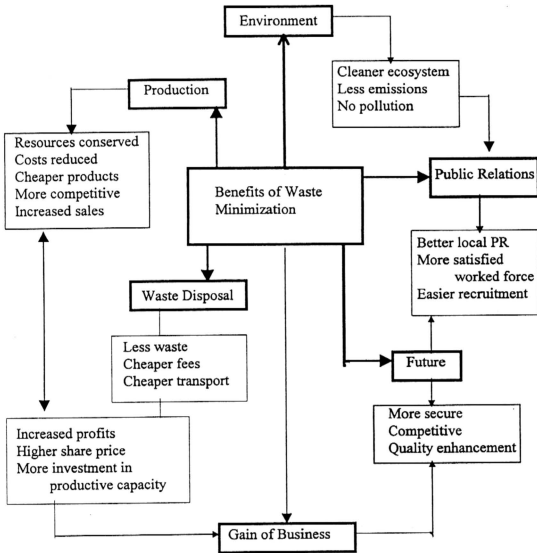
Figure 2.3 Various benefits accrued from implementation of waste minimization program
(Clark,1995)

2.2.4   Developing And Implementing Waste Minimization Program

US EPA (1988) developed a systematic, planned procedure of waste minimization which is suitable and applicable to all types of industries and processes. This procedure was further improved by Critenden and Kolaczkowski (1995). Petek and Glavic (1996)

proposed an integral approach which includes research at all levels of production in a company (organization, maintenance, process, production, distribution and utilization of energy) including optimization after changing environmental and economic conditions. In addition, Slater, *et al.* (1995) also proposed a method that can be used to analyze chemical process flowsheets for waste minimization options and pollution prevention index (PPI) that emphasizes EPA pollution prevention priorities.

A stepwise procedure to developing and implementing a waste minimization program is outlined in Figure 2.4 (Hunt and Schecter 1995). This procedure is suitable for all types and sizes of industries and flexible to be altered to meet local needs.

Obtainment of top management commitment, setting of realistic goals and timescales which are consistent with the policies adopted by top management at the beginning of the project are the key elements to a successful waste minimization program. A careful review of the plant's operations and waste streams are essential to develop options for reducing the types and amounts of waste generated. Then, technical and economical feasibility of the selected options are evaluated. Finally, the most promising alternatives are selected for implementation (Snider, 1992; Hunt and Schecter, 1995; Petek and Glavic, 1996).
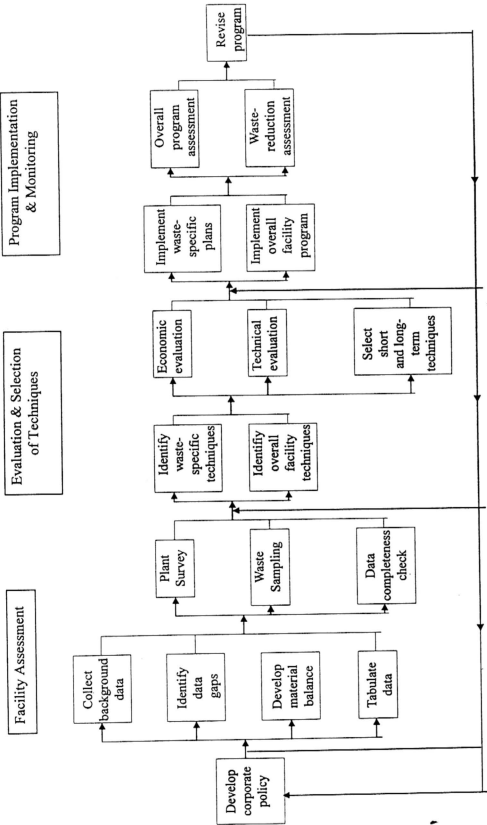
Figure 2.4 Approach of developing and implementing a waste minimization program (Hunt & Schecter, 1995)

2.2.5   WASTE AUDIT

The essential steps for successfully achieving the goal of waste minimization begins with a waste audit (EPA, 1990; LaGrega, *et al*., 1994; Sastry, 1995; Shen, 1995). A formal waste audit examines each operation that generates waste to determine how the waste is generated, what are the characteristics, how it is managed and what are the associated costs. This provides baseline condition for evaluating progress towards meeting waste minimization goals. It also provides necessary data to prioritize waste streams and to identify alternative options for minimizing the high-priority wastes (LaGrega, *et al*., 1994). This prioritization is generally based on composition, quantity, costs of disposal, degree of hazard, potential for minimization, recyclability and compliance status (Haas, 1995).

Various versions of waste audit have been established, however there are a few basic elements that are relevant to most of the waste generation scenarios (Resch, 1989; Hirschhorn and Oldenburg, 1989). A typical waste audit would comprise the following key components:

Step 1 : Identify the amounts and types of hazardous substances in wastes and
emissions, including both regulated and unregulated.

Step 2 : Identify the specific production sources of the wastes and emissions.

Step 3 : Set priorities for waste reduction action on the basis of costs, environmental
concern, worker health and safety, liabilities, and production constraints.

Step 4 : Analyze and select technically and economically feasible reduction techniques.

Step 5 : Compare the economies of waste reduction alternatives with current and future waste management or pollution control options.

Step 6 : Evaluate the progress and success of chosen waste reduction measures.

Hirschhorn and Oldenburg (1989) also suggested 4 stages of waste reduction audit (WRA) defined by the needs of waste reduction over time and to assess the applicability and scope of WRAs:

Stage 1: Common Sense Waste Reduction

Immediate reduction opportunities that are readily visible, common sense and low cost are identified through direct observation of the operating process. There are no technical barriers and it can be implemented in days and weeks. They often involve changes in procedures rather than changes in production technologies and major equipment. For examples, improving inventory controls, ceasing the commingling of hazardous with non-hazardous waste and reducing the amount of water consumed in cleaning equipment. This approach could stimulate waste reduction activities, educate production staffs and provide a record of actions and results.

Stage 2: Information-Driven Waste Reduction

This stage of waste reduction is relatively easy, quick, low cost, and no significant technological obstacles; but it does require more detail information about the generation of waste. Normally, it involves simple changes in production which is prompted by

production from similar successful industries. For example, replacing an organic solvent with a water-based solvent and installing a close-loop recycling unit.

Stage 3: Audit Dependent Waste Reduction

A formal waste audit is critical in this stage, where some technological obstacles are identified and technical and economical feasibility need to be studied. More capital investment become necessary and risk increases due to the uncertainty about economic payback and technical feasibility.

Stage 4: Research & Development Based Waste Reduction

Extensive research and development (R & D) on process technology or equipment and possibly product composition or design is required in this stage. Some circumstances like large waste stream from well established processes and wastes that seem inevitable unless a different product is design are favor a R & D effort. Careful and continuing economic analysis are required, including economic spinoffs and drawbacks should be thought about at the outset of the waste minimization. Waste reduction audit need to be carried out periodically for both the original situation and any new waste generating activity resulting from the R & D.

2.2.6   Waste Minimization Techniques

Waste minimization involves activities, practices or processes undertaken to avoid, eliminate or reduce wastes at its source of generation. Various versions of waste minimization techniques have been established since the promulgation of the related

environmental regulations. (Hirschhorn, 1988; Higgins, 1989; Hunt and Schecter, 1990; Karen, 1991; Englehardt, 1994; GECF, 1995). Generally, it can be classified into 3 generic categories: (i) prevention/source reduction, (ii) reuse/recycling/recovery, and (iii) waste treatment. An overview of techniques/strategies used in pollution prevention adopted from LaGrega, *et al.* (1994) is illustrated in Figure 2.5. This chart provides a clear establishment of priorities in hazardous waste management, ranging from product change to ultimate disposal of hazardous wastes. In practice, waste minimization strategies are usually used in combination so as to achieve maximum waste reduction.

I. Prevention/Source Reduction

Prevention from the source is the foremost component in the waste management hierarchy. This can be achieved by good practice (e.g. good operating practice, good engineering and maintenance and good housekeeping), production-process modification (including technology changes, product changes and input material changes) (Englehardt, 1994; Hunt and Schecter, 1995; Beck, 1997).

Early recognition of waste generation aspects during the process and product development stage is extremely important, and this constitute an important element towards the concept of clean technologies and clean products (Clift, 1997). This concept covers three complementary purposes: less pollutants discharges, less wastage and less demand on natural resources. The clean products should be designed in such a way that all the possible environmental adverse impact of the entire life-cycle of a product from the stage of manufacture, consumption and disposal are taken into consideration (Canda, 1993; Clark, 1995).
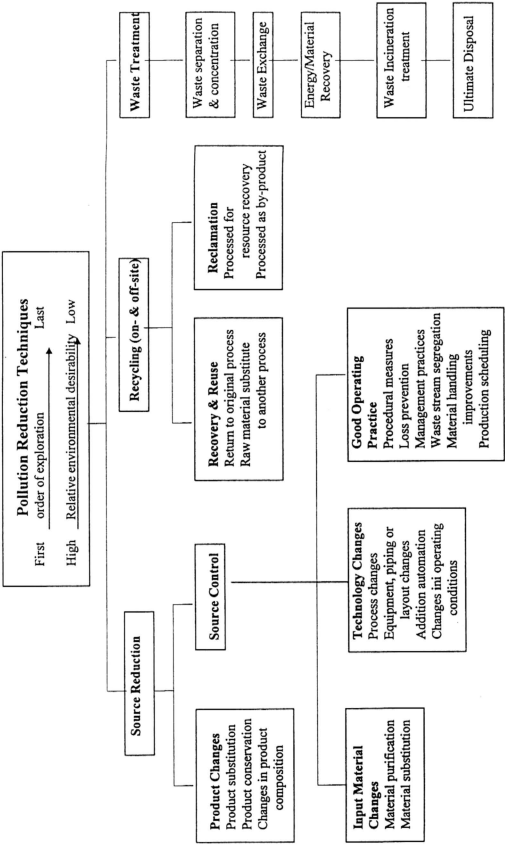
Pollution Reduction Techniques

First — order of exploration — Last

High — Relative environmental desirability — Low

Source Reduction

Source Control

Product Changes
Product substitution
Product conservation
Changes in product
composition

Input Material Changes
Material purification
Material substitution

Technology Changes
Process changes
Equipment, piping or
layout changes
Addition automation
Changes in operating
conditions

Good Operating Practice
Procedural measures
Loss prevention
Management practices
Waste stream segregation
Material handling
improvements
Production scheduling

Recycling (on- & off-site)

Recovery & Reuse
Return to original process
Raw material substitute
to another process

Reclamation
Processed for
resource recovery
Processed as by-product

Waste Treatment

Waste separation
& concentration

Waste Exchange

Energy/Material
Recovery

Waste Incineration
treatment

Ultimate Disposal

Figure 2.5 Waste Minimization Techniques (LaGrega et.al, 1994)

II. Recycling / Recovery

This is a desirable option when all other options for source reduction are exhausted. This can be a very cost-effective waste management alternative, whereby it eliminates waste disposal costs, reduces raw material purchased and provides income from a salable waste. Recycling is characterized by the following five major practices (Hass and Vamos, 1995):

(1). direct use or reuse of a waste material either to the originating process as a substitute for an input material, or to another process as an input material,

(2). recovery of a secondary material for a separate end use such as the recovery of a metal from a sludge,

(3). removal of impurities from a waste to obtain a relatively pure re-usable substance,

(4). energy recovery and

(5). utilization in pollution control system.

Whether or not recycling/recovery of waste materials is possible within a production process depends on a number of factors (Batstone, *et al.*, 1990):

1. quantity, quality, uniformity and properties of the waste materials,

2. options for the use or reuse of the waste materials,

3. availability and the price of the virgin or similar materials relative to the cost of recycling and storing the wastes,

4. availability of a specific technology to segregate recoverable and valuable materials from the waste (reclamation),

5. assessment (technical, economical and environmental) of the possible impact of the non-recovered waste materials,

6. assessment of long-term risks and liabilities, and

7. logistic constraints.

Toxicity of the waste does not appear to be a direct factor in the recyclability of a generated waste. However, the high volume wastes, which are often less toxic, are more commonly recycled. Wastes that have higher constituent concentration are usually selected for recovery and reclamation. Data suggest that there are threshold levels that must be reached before wastes can be considered eligible for the recycling process. For instance, the halogenated solvents content must be, on average, in the range of 35% to 40% of the generated waste before recovery or reuse technologies are practical (Batstone, *et al.*, 1990). Certain wastes that are not useful to a generator may be desired by another industry as a raw material. Waste exchanges are often helpful in facilitating the transfer and recycling of these wastes (Batstone, *et al.*, 1990; Donaldson, 1996).

Recycling of wastewater, contaminated solvent, oil and acids are common in many industries, such as textile (Petek and Glavic, 1996), semiconductor industry (Gilles and Loehr, 1994), pulp and paper mills (Sastry, 1995) and food industry (Beck, 1997). The recycling of glass bottles, paper and paperboard has become routine at most industries (Satchell, 1996) . Scrap metal such as swarf from machining operation is also a common candidate for recycling. Unfortunately, there is no information available on the recycling of the waste generated in friction material industries.

III. Waste Treatment

This is the least preferred option in the waste management hierarchy and only applied when all the other options are exhausted. Various waste treatment technologies

are available, ranging from biological treatment, physical-chemical processes, thermal methods to land disposal (Freeman and Harris, 1996). Choices depend upon the waste characteristics, degree of toxicity, treatment objective, economic considerations and regulatory requirements/standards.

2.3   WASTE MINIMIZATION PROGRAM IN MALAYSIA

In Malaysian industry, there isn't any structured waste minimization program promulgated by DOE (Argome National Laboratory and East-West Center, 1994). The use of cleaner production or waste minimization is still in an infant stage even though industries are generally aware of the benefits accrued from the incorporation of waste minimization practices in manufacturing process. Recycling of wastewater in rubber industry is considered as an example of cleaner production in Malaysia (UNEP, 1995). Perhaps the launching of the Hibiscus Award in 1996 was considered as the beginning point in the effort to promote cleaner technologies and industrial waste minimization program in Malaysia.

The Hibiscus Award is the premier environmental award in Malaysia, given in recognition of companies' initiatives and efforts in protecting the environment by incorporating good environmental practices and cleaner technologies. It is organized jointly by Environmental Management and Research Association of Malaysia (ENSEARCH), Malaysian International Chamber of Commerce and Industry (MICCI), Business Council for Sustainable Development in Malaysia and Federation of Malaysian Manufacturers (FMM), with the support of DOE (NST, 5 Nov.1997).

Given the multisectoral nature of the Malaysia industry, the organizers have decided that each year a few specific industries would be invited to vie for the Hibiscus Award. In 1996, the chemical and petroleum as well as the electrical and electronics sectors were judged, whereas in 1997, the focus was on textile, food and beverage, pulp and paper as well as hotel and resort sectors (NST, 5 Nov 1997).

According to a report prepared by the Argome National Laboratory and the East-West Center (1994), many incentives exist that encourage investment in pollution control equipment rather than waste minimization technology. For instance, a factory may receive an investment tax credit, an import duty exemption, an accelerated depreciation allowance, or a reduced interest loan for purchasing end-of-pipe environmental control equipment, but the same incentives are not available for purchases of cleaner production equipment.

The Federation of Malaysian Manufacturers (FMM) has expressed an interest in developing waste minimization information programs for its members. It has also suggested that the tax law be modified to allow credits for cleaner production/waste minimization technology (Argome National Laboratory and East-West Center, 1994).

2.4   WASTE MINIMIZATION IN OTHER COUNTRIES

Reflecting both an interest in saving and avoidance of prosecution from increasingly stronger environmental regulations, various industries around the world have

incorporated waste minimization practices in their operations and production. Many successful examples have been reported from both developed and developing countries (Freeman, *et al.*, 1990; Critenden and Kolaczkowski, 1995; Shen, 1995).

Development of waste minimization in UK, North America and European Union have achieved significant milestone (Smith, 1997). In US, waste minimization has its origins in the Resource Recovery and Reauthorization Act (RCRA), since 1976. In addition to traditional legislative mechanisms, the EPA has built co-operative partnerships with businesses, citizen groups, state and local governments, universities and trade associations. Among the collaborative efforts are 33/50, Waste Wi$e, Green Lights, Energy Star, WAVE, Design for the Environment and Project XL.

The introduction of integrated pollution control (IPC) into UK legislative mechanisms has led to the adoption of waste minimization initiatives across all prescribed processes and many other processes. Aire and Calder Project in Yorkshire and Project Catalyst are among the successful projects which reduced the demand of water by 1.9 million m^3 per year and a potential saving of 1.8 million tonne of liquid effluent (Johnston, 1994; Atkins, 1994; UNEP, 1995).

Japan is considered as a technologically-advanced country in Asia. Japan can probably be considered the world's premiere recycling country. This is due to (i) its limited space and resources, (ii) its enormous reliance on imported primary raw materials (including 98.8% of its oil and 99% of its iron ore), (iii) the need to control pollutants from various industrial activities and (iv) government support. These factors being to

shape waste management policies in Japan and has resulted in the implementation of many creative and sophisticated techniques (Englande, 1994).

In Taiwan, a developing nation, a national Industry Waste Minimization (IWM) master plan was approved in July 1990, which called for an aggressive program to demonstrate IWM techniques and to provide technical assistance and consultation to the industry. The total estimated benefit accrued from this program was over US$70 million from 1991 to 1994 (IWM in Taiwan, R.O.C.,1995).

2.5   SOLIDIFICATION/STABILIZATION TECHNOLOGIES

Solidification/Stabilization (S/S) is a term often used to designate a technology employing additive(s) to reduce the mobility of pollutants, thereby making the waste acceptable under current land disposal requirements (Wiles, 1989). S/S technologies have been widely applied in waste treatment for a wide variety of hazardous waste materials, such as spent pickle liquor, industrial sludges, filtered cakes, contaminated ashes and soils. It is also effective in immobilizing many low-level radioactive wastes (Freeman and Harris, 1996). In fact, many of the approaches used in solidifying/stabilizing hazardous industrial wastes originated from radioactive waste management (Pojasek, 1979; Zamorani, 1994).

S/S technology is a viable technical option which has historically proven to be cost effective and it has been specified by EPA as Best Demonstrated Available Technologies (BDAT) for a number of waste streams and some can be used as a basis for

"delisting" a waste as hazardous under RCRA (Bishop, 1995; Means, *et al.*, 1996; EPA Engineering Bulletin, 1992 & 1997).

S/S processes are intended for use in situations where chemical detoxification of a hazardous waste stream is either not technically applicable or prohibitively expensive (Powell and Mahalingam, 1992). These techniques are often chosen for wastes with poor handling characteristics (e.g. dusts, viscous sludges) or for large volume of wastes that are difficult to treat using other technologies (e.g. power plant desulfurization sludges).

Although the terms stabilization and solidification are often used interchangeably, they represent different concepts in waste treatment. Stabilization refers to techniques that attempt to reduce the solubility, mobility, and/or chemical reactivity of hazardous waste by changing its chemical state or by physical entrapment; whereas solidification refers to techniques that mechanically bind/encapsulate the waste in a monolithic solid of high structural integrity in order to restrict migration of hazardous constituents (Wiles, 1989; LaGrega, *et al.*, 1994; Bishops, 1995; Freeman and Harris, 1996). Typically, stabilization processes also involve some form of physical solidification, however, solidification may or may not involve a chemical bonding between the hazardous contaminant and the additives (Wiles, 1987; Bishops, 1995).

Briefly described, S/S technologies utilize a range of combined physico-chemical processes to transform hazardous waste materials to a solid matrix which enable long-term immobilization of the hazardous contaminants, by using appropriate binding agent/stabilizer, so as to ensure safe handling, transportation and storage with minimal

potential contamination of the environment. The form of the final product from S/S treatment can range from a crumbly, soil-like mixture to a monolithic block.

S/S methods are designed to accomplish one or more of the following objectives (Wiles, 1989; Bishops, 1995; Means, *et al.*, 1996; EPA Engineering Bulletin, 1997):

1. improve material handling and landfilling characteristics of the sludges or dust from which they are derived, by forming a monolith;

2. reduce the hazardous constituents solubility by formation of sorbed species or insoluble precipitates (e.g. hydroxides, carbonates, silicates, phosphates, sulfates or sulfide);

3. decrease the exposed surface area and the porosity of the waste by formation of a crystalline, glassy or polymeric framework which encapsulates the waste particles, and

4. inhibit the contact between transfer fluids and contaminants by reducing the materials permeability.

S/S technologies are often categorized on the basis of the similarity of the principal binders used. The binder systems can be divided into two broad categories: inorganic or organic. Inorganic binder systems include varying combinations of hydraulic cements, pozzolan, lime, silicates, fly ash and gypsum. Organic binders used or experimented include urea-formaldehye, thermoplastics (e.g. bitumen/asphalt, polyolefins

- primarily polyethylene and polybutadiene), thermoset polymer (e.g. epoxy), polyesters (Zamorani,1994; Bishops, 1995; Freeman and Harris, 1996).

Combination of both type of systems have also been used, for example, diatomaceous earth with cement and polystyrene, polyurethane and cement, polymer gels with silicates and lime-cement with organic modified clays (Wiles, 1989 and 1992; De Franco, 1990; Bishops, 1995; Means, *et al.*, 1996).

Commercial vendors have typically developed generic processes into proprietary processes by adding special additives to provide better control of the S/S process or to enhance special chemical or physical properties of the treated waste in order to ensure environmentally safe ultimate disposal of problematic industrial wastes (Pojasek, 1979; Zamorani, 1994; Freeman & Harris, 1996; EPA/ORIA, 1996). Table 2.2 summarizes some of the commercially available proprietary S/S technologies.

The specific technology used is based on several factors including the treatment objectives, waste characteristics (both chemical and physical), regulatory requirements, performance requirements, economics, resulting volume, logistic constraints, and material availability (Wiles, 1989 and 1992).

In addition, site specific factors such as location condition, climate and hydrogeology must also be taken into consideration to assure an acceptable performance.

Table 2.2 Summary of some commercially available proprietary S/S processes.

Proprietary S/S Process	Descriptions
1. CALCILOX®[1]	• Particular wastes obtained in the mining, preparation and coal combustion (e.g. coal fines and flue gas desulfurization (FGD)) are treated with an additive named "Calcilox". • Calcilox additive is a dry, free-flowing, light-grey colored powder of inorganic nature and it's hydraulically active.
2. CHEMFIX®[1]	• Based on the reaction between the soluble silicates and silicate setting agents that react in a controlled manner to produce a solid matrix. • A cross-linked, 3-dimensional polymer matrix is formed which is similar to natural pyroxene minerals - high stability, high melting point, a rigid and friable structure.
3. TERRA-CRETE®[1]	• A unique waste-to-waste approach for the treatment of FGD sludges. • Utilizes 2 similar compound with cementitious properties that are obtained from the FGD sludge itself - gypsum ($CaSO_4$) and Calcium sulfite ($CaSO_3$).
4. TERRA-TITE®[1]	• Utilizes cementitious additives. • The products exhibits low permeability, high strength and insignificant leachability. • Specially designed to treat waste containing Hg, Cr, Ar and organic wastes.
5. SEALOSAFE®[1]	• Utilizes calcium containing cement and aluminate and/or alumino silicate to mix with waste dissolved in water to produce a product, called STABLEX. • It exhibited superior properties in terms of low leachability, low permeability and high strength.
6. Separation and Recovery System / Ecology of France (SRS/EIF) Process[2]	• Utilizes lime-based process to permanently fix waste in a matrix product. • Particularly good for treating waste with high organic content, e.g. refinery intermediates of final products, halogenated chemicals, PCBs, pesticides, painting waste and acid sludges.
7. Sulfur Polymer Encapsulation (SPE)[3]	• A thermoplastic material. • It has a relatively low melting point (120ºC) and melt viscosity (about 25 centipoise) and thus can be processed easily by a simple heated stirred mixer. • Higher compressive and tensile strength
8. Phoenix Ash Technology (PAT)[3]	• Involves the conversion of a mixture of fly ash, volcanic ash or kiln dust into a solid form, typically brick. • relies on mechanical compression during the initial onset of hydration, and uses lower moisture levels than cementitious slurry. • Applicable to wide variety of materials, particularly viable for fine inorganic materials.

Sources: 1. Pojasek, 1979; Zamorani, 1993; 2. De Franco, 1990; 3. EPA/ORIA, 1996.

This review will focus on both inorganic and organic-based systems, in particular, cement-based process and polymer encapsulation respectively, since they have been employed in this project.

2.5.1   Grout/Cement Based Techniques

Cement-based stabilization/solidification is one of the most prevalently used techniques because of the relatively simple and inexpensive nature, compatibility with wide variety of disposal scenarios, and ability to meet stringent processing and performance requirements. This technique is also commonly called grouting, and the mixtures so obtained, grouts (EPA/ORIA 1996).

Cementitious materials include cement, ground granulated blast furnace slag, flyash, lime, cement kiln dust and silica fume. Various combinations of the cementitious material, and other proprietary additives are mixed with wastes to improve waste-form performance, such as enhancing the immobilization of contaminants, increase the compressive strength, eliminate free liquids and reduce the resulting volume increase.

Among these, ordinary portland cement (OPC) is the most commonly used binding agent, which reacts with water to form a solid product. OPC typically consist of calcium silicates, aluminates, aluminoferrites and sulfates. Waste materials are mixed with cement followed by the addition of water for hydration. The hydration reaction of the cement forms a variety of compounds as the cement paste sets, including calcium

hydroxides and calcium silicate hydrates, which results in rock-like, monolith and hardened mass. The former provides large amount of entrapped alkaline materials, while the latter supplies the cement's structural stability (Bishops, 1995).

According to Cocke's (1990) delineation on the chemical and physical aspects of cement-based system, the hydration reaction results in several chemical and physical mechanisms that combine, capture and/or immobilize waste contaminant. The chemical mechanisms involve chemical change (transformation of soluble salt of hazardous metal to a relatively insoluble silicate, hydroxide or carbonate form), chemical incorporation within an insoluble crystalline structure, chemical adsorption, precipitation, or form a surface compound to any of several cement component surfaces. The physical mechanisms involve the capture (microencapsulation) of hazardous constituent within the resulting physical structure of the solidified waste matrix.

Although the cement-based S/S technique has an extensively documented history and a well established technology, many fundamental aspects, such as the chemical mechanisms of hydration, the bonding between waste material with cement and detailed microstructural and microchemical studies of OPC are still poorly understood and lack quantification (Glasser,1997).

In cement based S/S, the engineering properties of the solid matrix formed from the treatment of the waste are highly dependent on the water/cement (W/C) ratio and the degree of hydration of the cement (Zamorani, 1993). The cement is sufficiently hydrated at W/C ratio of 0.48 by weight, leaving some free pore water, gel water and air voids.

Porosity increases rapidly and the strength declines as the W/C ratio increases greatly above 0.48, hence leading to higher leaching rates (Bishop, 1995). However, a minimum of about 10% cement on W/W basis is generally required to produce a cured solid product with the necessary mechanical strength (Batstone, *et al.*, 1989).

Inorganic Waste

Generally cement-based S/S is suitable as a treatment alternative for materials containing inorganics, semi-volatiles and/or non-volatile organics. The effectiveness of cement-based system to immobilize heavy metal wastes, as well as soils and sludges contaminated with heavy metals, has been repeatedly demonstrated, in both laboratory experiments and cleaning contaminated sites (Freeman and Harris, 1995).

Shively, *et al.* (1986) and Conner (1990) indicate that most cement-based waste forms are initially at pH 10 - 11, as a result, the metals are retained in the form of insoluble hydroxide or carbonate salts within the hardened structure. In another words, the naturally high pH values are usually desirable for heavy metal (e.g. As, Cr, Ni, Cu, Zn) immobilization because most metal hydroxides have minimum solubility in the pH range of 7.5 - 11. Some metals, for example lead, is amphoteric - shows higher solubility at both low and high pH, but on the other hand, insoluble at pH 7 to 11 (Shively, *et al.*, 1986; Conner, 1990; Bishop, 1995).

Organic Waste

The opportunities to capture and immobilize organic materials in cement-based solidification process are limited (Jones, 1990). Due to the hydrophobic nature of many

organic waste materials and the surface tension effects, organic compounds (e.g. oil, grease, Trichloroethylene, phenol, etc) tend to retard cementitious reactions, inhibiting the formation of solid monolith mass and easily leached from the waste forms (Freeman and Harris, 1996; Bishops, 1995). As a result, it reduced the final strength and is not easily stabilized. They may also reduce the crystalline structure formation resulting in a more amorphorous material.

Organics, even in small amounts, can interfere in the performance of S/S processes. However, at what concentration the organic will interfere with the cementitious reaction is still questionable (Vipulanandan and Krishnan, 1990). Conner (1990) reported that cement-based S/S works satisfactorily for liquid and sludge wastes with up to 15% (by volume) of organic constituent.

Research have been conducted into the use of various additives (e.g. organically modified and natural clays, vermiculite and soluble sodium silicates) in order to reduce the organic contaminants' interference with cement hydration and enhance stabilization (Brown, et al., 1992; Lo, et al., 1997). Recent investigations have indicated that true bonding occurs between organically modified clays and phenol (Soundararajan, et al.,1990).

Clay materials, such as bentonite, with their high cation-exchange capacity and extensive specific surface, are often used to extend the range of wastes suitable for fixation to inorganic wastes containing up to 5% of organics. Vermiculite and montmorillonite clays which have cation-exchange capacities in the range of 130 to 150

meq per 100g also demonstrate their adsorptive capacities for organic compound (Batstone, *et al.*, 1989).

For solidification of mixed waste, extensive research has been carried out over the years, including the use of activated carbon, exchanged clays (Pollard, *et al.*, 1991) and zeolite (Cullinane and Jones, 1989; Cioffi, *et al.*, 1996).

The advantages and disadvantages of cement-based S/S is presented as Table 2.3.

Table 2.3 Summary of advantages and disadvantages of cementitious S/S processes

	Advantages	Disadvantages
1.	Low capital investment of equipment and operating costs	Large amount of raw materials are required
2.	Materials needed are relatively cheap and easily obtainable	Weight and volume increase of treated product, hence increased transportation and disposal costs
3.	Techniques for processing are relatively well established and compatible to a wide variety of disposal scenarios	Imcompactable with certain types of waste, particularly those containing organic compounds, that may retards setting
4.	Natural alkalinity of cement helps to neutralize acidic waste	Treated waste are relatively vulnerable to leaching, especially mild acids, additional sealant may be required
5.	Extensive dewatering of wet sludges or waste is not necessary as water is required for hydration	Mechanism of stabilization not well established
6.	Physical properties of treated waste can be varied from soft clay to a monolithic material by selectively varying the ratio of binding agent	

Sources: Batstone, *et al.*, 1989; LaGrega, *et al.*, 1994.

2.5.2 Polymer Encapsulation

The polymer encapsulation is a relatively new technology (Powell and Mahalingam, 1992). This is a viable treatment option for a variety of mixed waste streams containing arsenic, heavy metals, inorganic salts, polychlorinated biphenyls and dioxins. It is particularly well suited to treat water-soluble salts, such as chlorides and sulfates that generally are difficult to immobilize in a cement-based system (EPA/ORIA, 1996; Engineering Bulletin, 1997).

Polymers with their rapid-setting, high-strength and elasticity, high impermeability and high corrosive resistance appear to be an effective mean of reducing leachability of stabilized/solidified waste matrix prior to disposal into landfill. In addition, most of these systems are hydrophobic after curing and tend to resist leaching even if crushed to small particle size. This is particularly good at immobilizing highly toxic waste constituents whose leaching must be limited to part per billion (ppb) range (Conner,1990). Cullinane and Jones (1989) have clearly stated the need for fundamental research (mechanisms of immobilization and release of contaminants) to better understand the performance of organic polymers and other binders in the S/S of organic wastes.

Two classes of polymers, thermoplastic and thermosetting, have been applied to waste encapsulation.

Thermoplastic Processes

Thermoplastic polymers are organic plastic capable of reversibility and become liquids and solids upon heating and cooling (Pojasek, 1979). Thermoplastic materials include asphalt, paraffin, bitumen, polyethylene, polypropylene and wax. Of these, asphalt is the most commonly used and least expensive (LaGrega, *et al.*, 1994). In addition, sulfur has been incorporated in the encapsulating matrix to improve physical strength and structural integrity. The stabilized wastes are quite resistant to leaching and biodegradation (Batstone, *et al.*, 1989).

The waste materials need to be either dry or dewatered to a high solid content and is then mixed with the polymer at an elevated temperature (130 - 230°C) in an extrusion machine. The mixture is then discharged from the extruder into a drum or other containers (EPA Engineering Bulletin, 1997). When cooled, the solidified materials are characterized as a thermoplastically coated waste and packed for ultimate disposal. No interaction occurs between the waste and the polymer.

Thermosetting Processes

Thermoset materials become solid and harden when heated. They remain solid even after subsequent heating and cooling cycle. Thermoset resins, such as epoxy and urea-formaldehye, relies on polymer formation to immobilize waste constituents. Organic monomers are thoroughly mixed with the waste and the promoter/curing agent is then added to initiate polymerization. Cross-linking reaction is influenced by parameters such

as pH, water content, ionic constituents in feedstreams, temperature and homogeneous dispersion of curing agent in the mixture (Pojasek, 1979).

The principal advantage of this process is that it generally results in a low-density material relative to other fixation techniques and small quantities of additives are required to solidify the wastes (LaGrega, *et al.*, 1994). However, the potential reaction between waste constituents with monomer and curing agent may interfere with the solidification reaction that makes thermoset polymers a less desirable than thermoplastic extrusion for particulate wastes such as salts and sludges (EPA/ORIA, 1996).

Many studies have been conducted on polymeric encapsulation. Researchers in Washington State University have successfully used water-extensible polyesters in solidifying low-level radioactive wastes and wide spectrum of toxic chemical waste such as arsenic, cyanide, PCB, toxic metals and pharmaceutical wastes (Subramaniam and Mahalingam, 1979). Kim, *et al.* (1992) have successfully solidified dried borate waste using polyester to produce a high integrity monolith with very low diffusion coefficient.

In addition, Breslin and Tisdell (1994) successfully used high-density polyethylene and polystyrene resin to retard the leaching of metals and salts associated with combustor ash. Sulfur Polymer Cement (SPC), a thermoplastic material, has demonstrated superior properties like high compressive and tensile strength, low melting point (120ºC) and melt viscosity (about 25 centipoise). It has been used to develop a process for treatment of radioactive, hazardous and mixed waste in Brookhaven National Laboratory (BNL) (EPA/ORIA, 1996).

Table 2.4 summarizes the available information on the relative merits and disadvantages of polymeric encapsulation processes.

Table 2.4 Summary of advantages and disadvantages of polymeric encapsulation processes

	Advantages	Disadvantages
1.	Higher isolation of waste constituents from surroundings because formation of impermeable boundary	Materials used are more expensive, require skilled labor and expensive equipment.
2.	Less additive is required	Large expenditure of energy in drying, fusing and polymerization
3.	Treated materials are of lower density, hence reducing transportation and disposal costs	Some organic polymers are flammable
4.	Processes can encapsulate wider range of waste	Materials are biodegradable and liable to attack by organic solvents
5.	For macro-encapsulation, state-of-art of spray on equipment for resin application may be employed directly and does not require expenditure of energy.	Incomplete polymerization of some of these materials could itself cause pollution

Source: Batstone *et al.*, 1989.

2.5.3   Evaluating Performance of S/S

A wide range of performance tests may be used in conjunction with S/S treatability studies to evaluate short- and long-term stability of the treated waste. These include total waste analysis for organics, leachability studies using various methods, permeability, unconfined compressive strength (UCS), treated waste and/or leachate

toxicity endpoints and durability test (freeze/thaw and wet/dry weathering cycle tests) (LaGrega, *et al.*, 1994; Means, *et al.*, 1995; Freeman and Harris, 1996).

In addition, Grube (1992) has described and discussed the application of physical and morphological measures to help determine the effectiveness of solidification/stabilization technologies through laboratory testing and observation and analysis of visible characteristics and their changes.

Leaching Tests

Leaching, which can occur when water contacts a solidified waste form, is an important mechanism for the dispersal of hazardous or other undesirable constituents into the environment via the leachate. Leach testing has thus been recognized as a primary and the most widely used indicator for evaluating the retention capacity of stabilized/solidified waste mass.

Leaching test should be designed to simulate the actual environmental conditions in the disposal site (Albino, *et al.*, 1996). However, in view of the variety of possible landfill scenarios, no single leach testing procedure or protocol can duplicate all possible field conditions. Ideally, the treated waste would be leach-tested with the surface-, ground- or rainwater that is present at that site. As alternatives, water, aqueous solutions of acids and salts, or organic liquids to model various disposal scenarios may be used in leaching tests, to determine waste composition, measure diffusion coefficients, or for other specific test purposes.

During the past, much effort have been devoted to understanding basic leaching mechanisms and long term leaching behavior as well as developing methodologies to determine the leachability characteristics of solidified matrix. However, many are still not yet completely clarified.

Studies have demonstrated that a great number of test factors or variables affect the leachability characteristics of solidified/stabilized products. The major factors include surface area of the waste, alkalinity of the solidified/stabilized product, physical nature of the waste (monolithic, crushed or pulverized), type of liquid-solid contact (static, dynamic or in flow), type of leachant (distilled water, acetic acid or simulated acid rain), extent of mixing/agitation, leachant-to-waste ratio, waste and leachant contact time, number of elutions used, extraction vessel, temperature and pH adjustments (Conner, 1990; Albino, et al., 1996).

Literature review indicates that many leaching tests have been established. Summary of various leaching test procedures or protocols has been prepared by several authors/agencies, such as EPA (1979), Hannak, et al. (1988), Planning Research Corporation (PRC), (1988), Conner (1990), LaGrega, et al. (1994) and Means et al. (1995). Generally, these leaching tests can be categorized as: (a) extraction tests, (b) leach tests and (c) column leach tests (Sharma and Lewis, 1994).

(a). ***Extraction tests*** (e.g. Toxicity Characteristics Leaching Procedures (TCLP), Extraction Procedure (EP) Toxicity Tests), are batch procedures and generally involve agitation of ground or pulverized wastes (particle size < 9.5mm) in a leachant to achieve continuous mixing, for a specified period of time. The leachant may be acidic or neutral, in most cases is diluted acid. Extraction normally lasts from hours to days and are therefore short-term tests. It should be noted that most of the extraction tests use a leachant-to-waste ratio of 20:1, so that the maximum concentration of contaminants that can be attained in the leachate is 5% of that in the original solid.

Studies have shown that the final pH of the leachate is one of the prime controlling factors in metal leaching. With the larger surface area exposed to the leachant, the extraction tests are designed to simulate the leaching potential of a contaminant in a "mismanagement" leaching scenario, where it is disposed in a landfill designed for municipal refuse. Such landfills are known to generate organic acids during decomposition of organic matter in the refuse and the use of acetic acid in the leachant is to simulate those acids (Blackburn, *et al.*, 1988; Conner, 1990; Reynolds, 1991).

The TCLP test has been commonly used by US EPA and state agencies to evaluate the leaching potential of S/S treated waste. It is a second generation extraction procedure which improves upon the existing EP technique and allows for the inclusion of an expanded list of volatile and semi-volatile organic compounds. It should be highlighted that the same test is also being used in Bukit Nanas Integrated Hazardous Waste Management Center, Malaysia.

Recent studies show a significant effect of curing time on both TCLP results and the chemical structure of the stabilized waste, as evidenced by spectroscopic analyses and these observations underline the limitations of the TCLP test as an indicator of the long-term leaching of stabilized wastes.

(b). ***Leach testing*** involves no agitation of monolithic waste mass. Leach tests may be run under two conditions: (i). static condition - the leachant is not replaced by a fresh solution, assuming leaching takes place under static hydraulic conditions, or (ii). semi-dynamic leaching conditions - the leachant is sampled and replaced with new leachant at designated intervals (e.g. American Nuclear Society Leach Test (ANSI/ANS 16.1)), assuming leaching takes place under nonequilibrium conditions. The leach tests on monolith specimens are often used to simulate leaching conditions under well managed landfill sites (Cote and Hamiton, 1983).

The ANSI/ANS 16.1 is intended mainly to develop a figure-of-merit (Leachability Index) for comparing the leaching resistance of S/S treated waste and also to indicate contaminant release rate. This leaching protocol assumes that internal bulk diffusion from a semi-infinite medium is the most likely rate-determining mechanism during the initial phases of the leaching process, and concentration of the species leached is zero at the surface of the waste form after leaching commences.

(c). **Column leach tests** involves placing pulverized waste in a column, where it continuously contacts a leaching solution at a predetermined rate. Column testing is considered to be more representative of field leaching conditions, however, because of certain factors such as channeling effects, nonuniform packing of waste materials, biological growth and clogging of the column, these tests has a reproducibility problem and has not been widely used (Sharma and Lewis, 1994).

Compressive Strength (CS)

This is a physical parameter that indicates the long term stability of a solidified matrix. Stabilized/solidified materials must have adequate strength to enable them to support the load of materials placed over them.

In addition, the test result would be expected to correlate with the effectiveness of stabilization of inorganic waste as the inorganic constituents are tied up in the hydrating matrix (Grube, 1992; LaGrega, *et al.*, 1994). Current US EPA regulation requires that the stabilized/solidified products have a minimum of 28-days unconfined compressive strength (UCS) of 50 psi.