ABSTRACT

The generation of waste in present situation ascertains the need for effective waste treatment. The application of waste in geotechnical construction works has been strongly recommended based on a viewpoint of the environmental geotechnics. In order to fulfill the technical, environmental and economical concerns, the specific criteria, designated as NICE criteria, was proposed as a guideline for the overall evaluation of wastes prior to their utilization. Many wastes were generally in agreement with NICE criteria and showed promising usage in geotechnical construction works with a wide range of applications. An overview of the research and development of recent decades on utilization of various kinds of waste is provided systematically. The intermediate treatment techniques for the geotechnical utilization are listed with their applicability to construction engineering field. Finally, the possible environmental impact during the reuse of waste is discussed. It should be noticed that the term waste is used here in a wide perspective, including different kinds of residues, with potential for utilization. In some countries the term waste is only used for materials that have to be disposed in a controlled manner, or may only be utilized after treatment to a “product”.

1.0 INTRODUCTION

Waste management should be conducted rationally based on an environmental geotechnical approach. Large amounts of waste are generated from various industries and activities of human being. Much of them are not being utilized, but are rather disposed of in the limited disposal sites available which will be exhausted in the near future. The hierarchy in waste management is waste minimization, proper treatment, reuse/recycling and energy recovery (Hartlén 1994). We should preserve natural resources and also minimize the need for landfilling. Utilization of wastes as construction or geotechnical material has been strongly recommended, and many attempts of geotechnical applications have been undertaken. Various kinds of ground improvement and soil stabilization techniques have been widely used to modify the engineering properties of waste for the geotechnical utilization as reported by Kamon and Katsumi (1994a).

The potential environmental risk by the geotechnical utilization of wastes needs to be avoided. Many waste materials might be contaminated by toxic and hazardous substances and require treatment for safe disposal. Geotechnical waste utilization can serve not only to prevent the negative environmental impact but also to preserve and protect nature. In this paper, our responsibilities are discussed in regard to waste utilization for a better environment.

2.0 CLASSIFICATION OF WASTE

2.1 Japanese Definition

Waste refers to refuse, bulky refuse, ashes, sludge, human excreta, waste oil, waste acid and alkali, carcasses and other filthy and unnecessary matter. Radioactive waste materials are often excluded from these categories because the specific control needs. Waste can be divided into two categories, domestic and industrial. Each may be managed by local government and/or private enterprise. Figure 1 briefly shows the classification of waste under the Japanese law. At present, large amounts of surplus soil and excavated soil are generated by the construction industry. Disposal sites for dumping waste are quite limited and the
contamination of numerous sites due to hazardous waste has been detected. It is therefore considered that
great benefits will be obtained if the reutilization of wastes achieves its optimum value whilst the adverse
impact, particularly in regards to environmental degradation, does not appear.

2.2 EU Directives
Two council directives and a proposed council directive can be considered relevant to the assessment of the
effects of use of secondary materials in construction.
Council directive on waste 91/156/EEC is concerned with measures to achieve a number of overall
objectives:
1) The prevention or reduction or waste production
2) The development of appropriate techniques for the final disposal of wastes to ensure that human health
   and the environment are not adversely affected
3) Stimulation of recycling, re-use or reclamation of wastes
4) The use of wastes as a source of energy

Waste is defined as any substance, which is contained in the European Waste Catalogue (annex 1 of the
Commission Decision 94/3/EC, establishing a list of wastes pursuant to Article 1 of council directive on
waste). The waste catalogue is not exhaustive. Further waste types may be added in the future. The catalogue
contains a listing of a large number of waste types in 20 categories:

Council directive on hazardous waste 91/689/EEC:
Hazardous waste is defined in this directive on the basis of Annexes. Annex I is a list of generic waste
types. Annex II contains a list of 51 substances or groups of substances which render wastes hazardous when
they have properties described in Annex III. Many substances, which commonly occur in secondary materials,
are included in this list.
The definitions of the hazard properties toxic, harmful, corrosive, irritant, carcinogenic, teratogenic and
mutagenic are given in the “Guide to the classification and labeling of dangerous substances and preparations”,
Regulations on Classifying and Labeling of Chemical Products are based on these directives.
Substances, which are classified as harmful according to one of the above categories, must exceed a defined
concentration in the waste for the waste to be classified as harmful. The concentration defined depends on the
definition of harmful, e.g. substances classified as very toxic must be present in concentrations exceed in 0.1%,
substances classified as toxic must exceed concentrations of 3% and substances classified as harmful must
exceed concentrations of 25%. A list of hazardous wastes has been drawn up based on the same waste
categories as the waste catalogue.

2.3 Classification and Criteria of Waste for Geotechnical Utilization
Since many waste materials might be contaminated by hazardous and toxic substances and most civil
engineering constructions are large-scale projects which require a great deal of materials, the major technical
characteristics of waste materials must be primarily focussed on prior to specific utilization. Accordingly,
specific criteria, designated as the NICE criteria, was proposed for the overall evaluation of certain wastes

![Fig. 1 Legal classification of waste and by-product in Japan](image-url)
in view of their effective utilization as follows (Nontananandh 1990, Kamon et al. 1991, Nontananandh and Kamon 2000):

(a) **Non-hazardous** waste material

Assessment on environmental suitability is very important since the utilization of waste may have high concentration of toxic or hazardous substances that may lead to other undesirable environmental impacts. For utilization with a high-level of confidence, wastes must be firstly classified as non-hazardous materials and must not lead to any pollution problems for a given application.

A waste is identified as harmful if it exhibits any of the following characteristics: toxicity, ignitability, corrosivity, and reactivity. Evaluation on environmental suitability can be accomplished based on the regulatory leaching tests. Since the available tests in the Netherlands present potentially maximum values of leakage characteristics and the applied conditions in geotechnical utilization are practically more stable. Therefore, if a waste is identified as a non-hazardous material, it exhibits promise for use with high reliability.

(b) **Waste with high Improvability**

As mentioned in the previous section, the current trend in environmental control and waste disposal is directed towards effective utilization of wastes by imposing more legal and moral restrictions on disposal, resulting in an increasing disposal costs and making alternative options more attractive. Also, introduction of waste tax is enhancing utilization. As a result, attention has been paid to certain types of waste utilization as a construction material in geotechnical engineering works, of which the demands are increasing yearly. In addition, it is considered that soil stabilization and ground improvement techniques can contribute significantly for the effective utilization of wastes. Possible modes of application are described in a subsequent section.

In corresponding to the selected mode of application, it is desirable to utilize the waste with high improvability. It can be applicable for any waste that currently exhibits maximum potential to improve the workability during construction, to perform well in conjunction with other conventional materials such as cement, soil and aggregate, and to improve the overall properties of resultant materials. This includes waste with high stability and durability for both short and long term. As an example, quality waste may exhibit some favorable characteristics such as acceleration of early strength, reduction of heat of hydration, or improvement on resistance to sulfate attack when partially mixed with cement, lime and/or some additives (Nontananandh and Kamon 1996).

As a result, applications can be made with high appreciation when waste with high improvability is used. For all cases, the evaluation regarding the degree of improvement can be accomplished by performing laboratory and/or field testing.

(c) **Waste with high Consistency & Compatibility**

It has been realized that industrial wastes from different sources have different properties, particularly in respect to their chemical compositions. Wastes are susceptible to inherent variability in their properties even when they are produced from the same factory with same manufacturing process. It may not be possible to eliminate this problem, however, the quality of new materials can be controlled by strictly checking all relevant properties such as physical and chemical properties prior to each utilization. In view of this, detailed sampling and analysis of the properties of waste material must be performed periodically to determine its basic characteristics. Using the statistical data, the range of properties of wastes can be delineated and then the waste can be classified based on their quality. Evaluation has to be made carefully before it is accepted for applicable standards and specifications. It is therefore recommended that wastes with high consistent in properties, high compatibility with other materials, and less impurities are good quality wastes and are desirable to be used. Since geotechnical construction works are dealt with large volumes of materials, the exploration of exchangeable sources of waste material (i.e., interchangeability of waste) is needed to implement the continuity and to prevent the shortage of material supplies throughout the project.

(d) **Waste with high Economic feasibility**

Generally, waste is a discarded material from the manufacturing process and is considered as useless material that has no other intrinsic value. As a result of development of technology, many wastes can now be
put in a form by which they are recoverable, replaceable, and then stable. Construction cost is directly proportional to the unit cost of materials used. Therefore, utilizing low-cost material can considerably save the total cost of project. The economic feasibility of waste utilization depends on many factors, including the cost/benefit analysis in terms of economic, social, and environmental costs. Benefits gained from waste utilization are obvious since the cost of waste appears to be either less than that of natural material or much less than the cost to produce a new natural one. Measuring environmental costs is difficult, however, environmental gain can be attributed to the conservation of natural resources and energy, and to mitigation of waste exposed in the environment. Utilizing wastes will reach optimum economic advantages if they exhibit most of the following characteristics:

1. Waste with a low unit cost but high quality which can save the total construction costs,
2. Waste with available quantity for a project, easy to handle but does not easily deteriorate when stored or under change in environment,
3. Waste that can be used as an “as is-product” without any treatment or with appropriate cost comprised by additional processing for property modification, and
4. Waste that can be utilized in great quantity without any potentials for degradability of new materials and the environment.

Industrial wastes should be classified based on the generating industrial processes. For geotechnical utilization, classification should include the fate and related characteristics of wastes. For example, after treatment, waste materials are divided into three groups. Those generated by excavating or crushing (surplus soil, waste concrete powder, waste rock powder), those generated from incineration or melting (coal ash, iron slag, incinerator ash), and those left “as it is” without any treatment (waste slurry or sludge, waste oil).

The first group of wastes is generated from construction works in large quantities. Construction work generates several types of waste. For example, excavation in urban areas for the construction of lifelines, subways, etc. and in mountainous areas for dams and tunnels produces enormous amounts of surplus soil and waste sludge. We geotechnical engineers are expected to contribute in saving-resources and waste utilization, since these industries are responsible for the consumption of resources, manufacturing of goods, and discharging large amounts of waste materials.

Residues are generated by incineration or melting, which means thermal power generation, iron and steel smelting, and incineration treatment of waste sludge and municipal waste. The characteristics of these wastes depend on their raw materials, incineration temperature and time, and boiler system. They are classified roughly as; fly ash collected from fuel gas, bottom ash left at the bottom of boiler, and slag produced by melting. These wastes categorized in the first and second groups are considered to be stabilized by compaction or chemical additives, namely solidification, after which they can be utilized as road materials or in embankment.

The last group contains waste sludge, waste oil, waste plastics and so on, the treatment of which are very difficult for various technical and economic reasons.

For efficient utilization, the properties and generating conditions of various wastes must be taken into consideration. The former includes whether the waste material is inorganic or organic, whether it contains heavy metals, and so on. The latter refers to when, where, and how many waste materials are generated.

The main wastes are slag from the iron and steel industry, sludge from the chemical, paper, and glass industries, and coal ash from the electric supply works. In addition to construction rubbish, large amounts of waste sludge and surplus soil are discharged during the foundation works and dredging works.

Intermediate treatment methods include dehydration, screening, crushing, aggregating, solidification, combustion and melting. Combustion or incineration, which realizes volume reduction and sanitary resolution against harmful substances, is becoming more widely used. By reducing the organic content by incineration, the material will be stable over time as well. Sludge, which has high water content, is reduced in volume by dehydration as well as combustion while the melting method has been developed mainly for the treatment of sewage sludge. Unfortunately, rubbish from construction works is scarcely reduced by intermediate treatment. Table 1 shows the possible treatment methods of wastes, and their applications.
Slag and dust are reused, but sludge and construction rubbish generated in large quantities have not been well utilized. The principal areas of waste utilization are as follows.

### 3.0 POTENTIAL UTILIZATION OF WASTES

#### 3.1 Surplus Soil and Waste Slurry

Large amounts of by-products are generated from construction work. Surplus soil can be dealt with in three ways. Good quality surplus soil, such as sandy soil, is utilized as filling or for embankments without any treatment. Other kinds of surplus soil are reused after improvement. Lastly, some surplus soil is disposed of without being used with/without treatment. This is because an effective treatment system has not been established. Table 2 shows the classification of surplus soils. Slurry or sludge in the bottom line is regarded as industrial waste.

Although some waste slurry or sludge is reduced by intermediate treatment such as dehydration, the vast majority of it, together with dehydrated slurry are placed in disposal sites. One problem with waste slurry utilization was that the material treated for utilization was often regarded as waste and had to be disposed of in designated areas. Another problem is that we cannot divide these by-products into valuable soil and waste slurry and this has led to the illegal dumping of large amounts of waste sludge.

Surplus soil is most commonly utilized in road and reclamation embankments. The building of man-made islands and large-scale levees are planned and a large amount of surplus soil is expected to be reused in their construction. Moreover, good quality surplus soil can be utilized for road subbase, as foundation of embankments, filling or back fill, for protection of slopes, as well as for some kinds of embankments.
Some soil stabilization methods are applied to surplus soil utilization. The most widespread method employs chemical additives such as cement, lime and hygroscopic polymer, and surface activator. Lime stabilization methods have been applied for soil utilization systems developed by the Osaka City Government and Osaka Gas Co., Ltd. (Ninomiya et al. 1988 and 1996). Another method which recently gained acceptance is aging, where surplus soils are stored for long-term in a stockyard with occasional mixing to be improved naturally.

Miki et al. (1992) developed some methods for increasing the value of soil materials. The liquefied stabilized soil method, where the soil mixture blended with stabilizer and large amounts of water has flowability and hardening characteristics, allows for use as filling in underground pipe construction and as backfill in retaining walls (Kuno et al. 1996). Typical strength and flowable properties of the liquefied stabilized soil are shown in Fig. 2. Based on the full-scale tests, suitable flowing condition and adequate placement method were established, and then it has been popularly used in Japan.

The lightweight soil stabilization method, where surplus soils are mixed with lightweight materials such as Expanded polystyrene (EPS) or formed cement, is expected to be utilized for embankment and backfill. Soil mixtures stabilized with EPS and hardening materials have wet density and strength as 0.6-1.2 Mg/m³ and 50-200 kPa respectively. Hayashi et al. (1998) also reported the engineering properties of air foam and cement treated dredged soils. The method has been applied to lightweight embankments over soft ground and backfill of retaining wall. Pradhan et al. (1996) examined the possibility of using a light loam soil mixture with wood chips instead of waste EPS. They found that it could be used for embankment with low density (1.0-1.5 Mg/m³), moderate strength (130-360 kPa) and high permeability (10⁻¹ to 10⁻² cm/s).

The fiber mixing method, where soils or stabilized soils are mixed with fibers (0.02-0.1 mm in thickness and 3 cm in length), can produce persistent and durable soil materials against erosion and cracking. The geotextile reinforced soil method is available for embankment construction and involves reclaiming surplus soil with high water content. The bagged soil method, where non-woven fabric bags are filled with surplus soil and

<table>
<thead>
<tr>
<th>Class of soils</th>
<th>Content (type and state)</th>
<th>Cone penetration strength, ( q_c ) (kPa)</th>
<th>Water content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>sand or gravel</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2nd</td>
<td>sandy soil or gravelly soil</td>
<td>larger than 800</td>
<td>less than 30 %</td>
</tr>
<tr>
<td>3rd</td>
<td>silty soil or clay soil which can easily executed on.</td>
<td>larger than 400</td>
<td>about 40 %</td>
</tr>
<tr>
<td>4th</td>
<td>clay soil, expect for 3rd-class soil</td>
<td>larger than 200</td>
<td>40 - 80 %</td>
</tr>
<tr>
<td>Sludge</td>
<td>slurry state soil or sludge</td>
<td>less than 200</td>
<td>larger than 80 %</td>
</tr>
</tbody>
</table>

Fig. 2 Flowability and compressive strength of liquefied stabilized soil

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waste slurry, is being researched and could be used to construct underwater embankments or flexible bulkheads (Miki et al. 1996).

To effectively manage surplus soil utilization, a system with the following three components should be established: (1) setting-up plants for soil improvement to adjust the quality of soils, (2) security of stockyards to regulate the supplying time and demand of soils, and (3) organization of related data to optimize utilization. The conceptual outline of such utilization system is shown in Fig. 3. Some city governments and gas supply companies have developed and implemented surplus soil utilization systems since 1980s. In 1992, a utilization system with data-base related to soil generation and demand, stockyards and plants for soil improvement, was opened by the Tokyo City Government (Maeda 1992).

Waste slurry is a dredged spoil and by-product of the cast-in-place concrete pile method, continuous diaphragm walls method, shield tunneling method, and so on. It cannot be discharged into rivers and seas and can not be utilized in embankments as soil material. Wastewater includes water that discharges from tunnels and rain water collected in land development areas. Waste slurry and water are generally subjected to proper intermediate treatment, after which the treated water can be released into rivers or as sewage according to the environmental criteria (for example, listed in Table 3). Unfortunately, meeting the criteria for SS (suspended solids), pH, COD (chemical oxygen demands) and oil content is generally difficult. Soils and cakes produced by treatment are transported to landfill sites for disposal.

Utilization of waste slurry or sludge can be classified relating to the treatment methods as shown in Fig. 4 (Kawachi et al. 1996). They are summarized as (1) flowable materials for grouting or excavating slurry, (2) earthen materials for embankment or backfilling, (3) clay materials for cement or ceramic manufactures, and (4) granular materials for aggregate.

Figure 5 shows the general flow of waste slurry or sludge treatment. Some processes can be omitted and others must be added, depending on the characteristics of the waste, environmental criteria and the

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**Table 3 Examples of effluent standards in Japan**

<table>
<thead>
<tr>
<th></th>
<th>Water Pollution Control Law</th>
<th>Sewage Law</th>
<th>Environmental Standard by PNCBL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>River &amp; Lake</td>
<td>Sea</td>
<td>River &amp; Lake</td>
</tr>
<tr>
<td>SS (mg/l)</td>
<td>200</td>
<td>600</td>
<td>below 1 - below 25</td>
</tr>
<tr>
<td>pH</td>
<td>5 (5.8)</td>
<td>5 - 9</td>
<td>6.5 (6.0)</td>
</tr>
<tr>
<td>BOD (mg/l)</td>
<td>160 (120)</td>
<td>600</td>
<td>below 1 - below 10</td>
</tr>
<tr>
<td>COD (mg/l)</td>
<td>160 (120)</td>
<td>-</td>
<td>below 1 - below 8</td>
</tr>
<tr>
<td>Mineral oil (mg/l)</td>
<td>5</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>Animal oil (mg/l)</td>
<td>30</td>
<td>30</td>
<td>-</td>
</tr>
</tbody>
</table>
applicability of dehydrated soil or discharged water. Tsukada and Ogawa (1996) also proposed ongoing activities for waste sludge utilization as shown in Table 4.

Kamon and Katsumi (1994b) proposed the conceptual outline of waste sludge utilization system. It involves dehydration and solidification and results in efficient treatment, decrease in volume, stabilization, and recycling of resources. The selection of treatment method is carried out based on the qualities of waste sludge; the density and funnel-viscosity, universally measured to determine the character of sludge at the excavation sites. Density indicates the solid content of sludge. The funnel-viscosity is increased by the remaining bentonite and dispersant CMC, which indicate the possibility for or the effectiveness of dehydration treatment.Attempts for volume reduction by dehydrating a high solid content sludge is not always the best strategy from technical and economical point of view. Sludge with low density can be dehydrated easily, but sludge with high viscosity is difficult to dehydrate even if it has low density, because of the remaining dispersants. With the use of a high pressure dehydrator, the strength of dehydrated cakes can easily increase, and thus be directly utilized as embankment and subgrade material. Kamon et al. (1998) proposed a continuous dehydration-solidification treatment system by introducing a parameter, w/wL (water content of the sludge normalized by the liquid limit). Application of the treated sludge as an earthen material is reviewed in relation to the treatment level. Kawaguchi et al. (1998) developed a new effective treatment system for dewatering the waste bentonite slurry. They introduced a unique polymer flocculant to have higher efficiency in lowering water content.

<table>
<thead>
<tr>
<th>Utilization of</th>
<th>Utilization of clay materials</th>
<th>Utilization as earthen materials</th>
<th>Utilization as flowable materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>granular materials</td>
<td>Sand, Sand cover</td>
<td>Aggregate, Base-course, Sand drain</td>
<td></td>
</tr>
<tr>
<td>clay materials</td>
<td>Raw material for cement, Raw material for ceramic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>impervious materials</td>
<td>Embankment, Filling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>excavating slurry</td>
<td>Grouting, Filling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component adjustment</td>
<td>Dehydration</td>
<td>Solidification</td>
<td>Granular forming</td>
</tr>
</tbody>
</table>

**Fig. 4** Concept of relationship between treatment method and application of construction waste sludge (Kawachi et al. 1996)

**Fig. 5** Typical management flow of waste slurry or sludge
3.2 Waste Concrete and Waste Rock Powder

Waste concrete is generated when concrete structures such as buildings and bridges are demolished, repaired or constructed. Waste concrete can be divided into mass and powder. Although a small amount of waste concrete mass has been used as a substitute for rubble in road construction, larger quantities need to be utilized for reduction. Therefore, a system in which waste concrete mass can be reclaimed for use as concrete aggregate has been proposed (Fig. 6). Park et al. (1998) also proposed to reuse construction and building debris as base and subbase materials. The difficulty is to produce reclaimed aggregate to suit the material standards of desired engineering application. Special equipment has been developed to remove the cement component from the original aggregate. Another problem with this system is that waste concrete powder is generated during the production of reclaimed aggregate. It has been proposed that waste concrete powder stabilized by hardening and additive materials can be utilized as road subbase (Kamon et al. 1992, Shibata and Saito 1996).

<table>
<thead>
<tr>
<th>USE</th>
<th>TYPE OF WASTE</th>
<th>TREATMENT METHOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>•Backfill, etc.</td>
<td>•Clay •Waste Slurry</td>
<td>Sediments obtained by the coagulating sedimentation method from clay left after sand and gravel have been removed from excavated material or from slurry used in reverse circulation piles are dewatered using filter press. The dewatered material is granulated with an extrusiontype granulator and baked in a rotary kiln to produce 20 - 30 mm grains.</td>
</tr>
<tr>
<td>•Base course, etc.</td>
<td>•Sludge •Concrete fragments</td>
<td>Mixtures of crushed concrete and sludge or mud are stabilized with a cement stabilizer, and hardened mixtures are broken up.</td>
</tr>
<tr>
<td>•Lightweight aggregate</td>
<td>•Sludge</td>
<td>Powder of spontaneous combustibles is added to sludge or mud, and the mixture is let to burn in a vertical or other type of kiln. Since the combustible will burn away, the mixture will become a porous material usable as lightweight aggregate.</td>
</tr>
<tr>
<td>•Lightweight aggregate •Horticultural soil •Filter material</td>
<td>•Sand pit sludge •Sludge from stone cutting •Purification plant sludge •Bottom sediment</td>
<td>A foaming agent is added to a mixture of sand pit sludge and sludge produced by stone cutting or other materials to form 3 - 30 mm grains. The grains are dried, baked in a rotary kiln and cooled in a rotary cooler. Lightweight aggregate can be obtained by sieving the material thus obtained.</td>
</tr>
<tr>
<td>•Lightweight aggregate •Horticultural soil •Filter material</td>
<td>•Quarry sludge</td>
<td>Dewatered cakes of quarry sludge (sandstone, shale) and purification plant sludge are crushed and re-formed into 0.6 - 20 mm grains. The grains are dried, baked and foamed in a rotary kiln while the grains are being dried. The baked and foamed grains are then cooled in a rotary cooler and sieved to produce a material usable as lightweight aggregate, etc.</td>
</tr>
<tr>
<td>•Lightweight aggregate •Horticultural soil •Filter material</td>
<td>•Wastes containing cement</td>
<td>Dewatered cakes of cement-containing waste liquid are dried and pulverized. Aluminum sludge and calcareous stone powder are added to the pulverized material. After the mixture is baked and rapidly cooled, it is pulverized again to obtain this hydraulic material.</td>
</tr>
<tr>
<td>•Molten slag</td>
<td>•Sludge</td>
<td>Dried sludge and 15% or so steel dust are mixed and molten in a furnace. The molten mixture in put into alkaline hot water, and the solids thus obtained are crushed with an impact crusher to obtain slag aggregate.</td>
</tr>
<tr>
<td>•Base course, etc.</td>
<td>•Self – hardening sludge (cement – containing)</td>
<td>Porous and highly absorptive sand-like material manufactured by baking old paper ash is added to and mixed with self-hardening (cement-containing) sludge. The mixture is then improved to obtain a material usable as base course material, etc.</td>
</tr>
</tbody>
</table>
In Sweden, good experience has been achieved using crushed concrete in road and highway construction (Hartlén et al, 1999b). The problem may sometimes be to get a grain size distribution that fits to standard requirements. In a recent project in Sweden (SYSAV), crushing is made in steps, starting with a rotation crusher. Magnetic material is separated and a second crushing occurs, using a jawcrusher. The fractions 0-50, 50-100 and 100-300 mm grades are collected. The coarser material may, depending on market demands, be crushed to 0-25 mm using a cone crusher.

Due to environmental constraints, rubble produced in crusher plants has become an alternative to natural gravel. A huge volume of waste rock powder is generated as a by-product from crusher plants annually. The characteristics of waste rock powder depend on the mother rock; waste rock powder of limestone is used in cement due to its chemical composition, while silty sandstone is used as a filling material. Waste rock powder is non-hazardous and a valuable resource. Suitable methods for its utilization in large quantities for construction are currently under research. The waste rock powder of sandstone, which has large specific surface area and contains large amount of amorphous materials, increases the effect of lime stabilization of soils in which a low amount of fine particle or amorphous material is present (Nishida et al. 1992). Waste rock powder solidified by a newly developed stabilizer can potentially be utilized as a permeable subgrade of road and back filling for retaining walls. Using a new method called "Bagged WRP Method," non-woven fabric bags are filled with a dry mixture of waste rock powder and stabilizer, and solidified by soaking (Kamon and Katsumi 1994c). The advantage of this method is attributed to the light-weight relative to the conventional soil materials. Thus, this method is proposed to be applied to sunk-levee materials or seafloor ground improvement. Figure 7 illustrates application of the Bagged WRP Method in tidal flat construction.

Fig. 6  Management flow of waste concrete

Fig. 7  Application of the bagged WRP method to tidal flat construction (Kamon and Katsumi 1994)
3.3 Coal Ash

Coal ash (CA) is a by-product of thermal power plants. Coal fly ash (CFA) comprises 80% of all coal ash generated, and its recycling is one of the main themes of by-product utilization. CFA is mainly utilized in cement manufacturing, as a substitute raw material for clay in making cement or mixture of blended cement called fly ash-cement. The remaining 70% is disposed of and not reused. Recently, there has been an increase in the amount of poor quality CA due to the use of various types of raw coal and the effects of combustion conditions on the environment. It is expected that CA can be reused as ground materials in large quantities.

Examples of utilization of CA in the field of geotechnics (Hartlén et al. 1997) are:
1. embankments to foam ash lagoons,
2. land reclamation,
3. soil stabilization,
4. load bearing layers of highway subbases,
5. building foundations,
6. building materials,
7. light fill material

Pulverized coal combustion is the most popular method of coal combustion in electric generation plants. Pulverized coal fly ash (PCFA) is used solely as raw material for cement. Because CA contains silica, which leads to hardening when reacted with lime, the utilization of coal ash as a soil stabilizer with/without admixtures has been researched. One of the important characteristics of coal ash is its light weight, and it is expected to become more widely used as a lightweight soil material, for embankments or caisson filler. PCFA was used in the construction of 67m-diameter, 15m-high man-made islands for the Hakutcho Ohashi bridge (1380 m in length) project (Kawasaki et al. 1992). A slurry disposal system using the double mixing method, where PCFA is mixed with water twice, has been confirmed to be more effective than those of normal wet and dry disposal systems (Table 5). It demonstrates the relation between high density and high strength.

The use of fluidized bed combustion to generate independent electric power is becoming widespread in the chemical industry and at iron and steel manufacturing plants. This system causes less air pollution than ordinary methods, such as pulverized coal combustion, and various kinds of raw coal can be used. A comparison of the chemical component of PCFA and fluidized bed combustion coal fly (FBCA) ash is shown in Table 6. FBCA contains gypsum and lime due to the use of desulpherizer in the boiler. As such, its utilization as soil stabilizer has been researched (Kamon and Katsumi 1994b). Low combustion temperatures (800-1000 degree in Celsius) are used to minimize the air pollution although this leads to the generation of FBCA containing large amounts of unburned substances. Further, CA has the ability to absorb heavy metals and agricultural chemicals. Therefore, it is being considered for use as a liner material in waste disposal sites (e.g., Jeong and Lee 1996).

### Table 5 Comparison of the engineering properties from three different coal ash disposal systems

<table>
<thead>
<tr>
<th></th>
<th>Wet Disposal</th>
<th>Dry Disposal</th>
<th>Slurry Disposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope of formed ground (degree)</td>
<td>0</td>
<td>0-5</td>
<td>0-20</td>
</tr>
<tr>
<td>Dry density (Mg/m³)</td>
<td>0.75</td>
<td>0.85</td>
<td>1.07</td>
</tr>
<tr>
<td>ρ_d/ρ_max (%)</td>
<td>65</td>
<td>74</td>
<td>93</td>
</tr>
<tr>
<td>Compressive strength (kPa)</td>
<td>20</td>
<td>50</td>
<td>150</td>
</tr>
<tr>
<td>Leaching substances ratio (%)</td>
<td>65</td>
<td>50</td>
<td>6</td>
</tr>
</tbody>
</table>

### Table 6 Comparison of chemical composition of coal fly ash

<table>
<thead>
<tr>
<th></th>
<th>Pulverized Coal Fly Ash</th>
<th>Fluidized Bed Combustion Coal Fly Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂ (%)</td>
<td>50-55</td>
<td>25-40</td>
</tr>
<tr>
<td>Al₂O₃ (%)</td>
<td>25-30</td>
<td>15-25</td>
</tr>
<tr>
<td>Fe₂O₃ (%)</td>
<td>4-7</td>
<td>1-3</td>
</tr>
<tr>
<td>CaO (%)</td>
<td>4-7</td>
<td>10-30</td>
</tr>
<tr>
<td>MgO (%)</td>
<td>1-2</td>
<td>1-2</td>
</tr>
<tr>
<td>K₂O (%)</td>
<td>0-1</td>
<td>0-1</td>
</tr>
<tr>
<td>Na₂O (%)</td>
<td>1-2</td>
<td>0-1</td>
</tr>
<tr>
<td>SO₃ (%)</td>
<td>0-1</td>
<td>3-8</td>
</tr>
<tr>
<td>Ig-loss (%)</td>
<td>1-2</td>
<td>10-30</td>
</tr>
</tbody>
</table>
Although the coal ash is one of the traditional recycled materials, there are many recent reports on the physical and chemical properties of CA for the geotechnical reuse, and the in situ applications (Carling 1998, Kim et al. 1998, Shrivastava et al. 1998, Sivapullaiah et al. 1998, Tessari et al. 1998, Thomé et al. 1998, Tsuchiyama et al. 1998).

3.4 Iron, Steel, and Other Slags

Slags from the metallurgical industry has been reused as road material, cement material, fertilizer, pottery material and soil stabilizer. Iron and steel slags can be classified as blast furnace slag, converter furnace slag and electric arc furnace slag. Blast furnace (BF) slag is produced as by-product in iron-making process and converter furnace (CF) slag is produced in the purification of iron, while electric arc furnace (EAF) slag is generated from the steel making process using scrap iron as the main raw material. While the production of BF slag and CF slag have decreased in recent years, the generation of EAF slag is on the rise. BF slag generated are used in blended cement (50%), road subbase materials (25%) and concrete aggregate or soil materials (25%), so the BF slag is by-product regarded not as waste but as a resource.

CF slag exhibits properties of expansion during hydration, which makes utilization difficult; i.e. it expands in volume during the hydration of quicklime (CaO). Such expansion characteristics can be eliminated by aging, allowing for reuse as subbase or base materials, as gravel in asphalt concrete, and for soil stabilization. Takahashi et al. (1996) reported the in situ application of CF slag in port and harbour construction. Since CF slags have an advantage of their large unit weight (1.9-2.4 Mg/m³), they were used as filling material for cell revetment, pre-loading mound material and soil improvement instead of ordinary sand.

EAF slags have efflorescence and expansive characteristics like converter slags, and are therefore mostly disposed of in reclamation areas. However, it has been proven that such slags can be reused as construction materials following aging treatment (Kuwayama et al. 1992). EAF slags have been reused as subbase materials. Fällman and Hartlén (1996) reported an example of the EAF slag utilization in road construction. They applied the screened EAF slags and estimated the environmental impact by the leachate of heavy metals. According to the monitoring results of test embankment, leached amounts of chromium could be controlled by grain size distribution, and both increased oxidation and decreased pH are functions of increasing leachate of chromium. After these tests had been evaluated, the EAF slag has been allowed to be used in the county where the steel plant is located.

Some types of EAF slag form hydration products of calcium silicate hydrate and hydrated gehlenite on long term usage in the field. Thus, they not only continue to increase in volume but also exhibit hydraulic properties. It has been clarified that slags stabilized with cement admixture can be utilized as road materials (Kamon et al. 1993), while slags blended with cement are available for soil stabilization (Kamon and Nontananandh 1990).

Copper slag sand is produced from refining process of copper. Since copper slag is stable and has relatively large specific gravity, large friction and high permeability, it can be used as a drain material instead of sand and gravel. Kitazume et al. (1998) reported the research findings of laboratory and field tests, in which copper slag was used for sand drain and sand compaction pile methods. The copper slag sand has high applicability in the sand compaction pile method with its high strength.

3.5 Mining Waste

The engineering properties of mining waste are very similar to soil materials. The use of mining waste, therefore, has increased in place of natural soils as a construction material for embankment at roadways, railways, rivers and dams over 20 years (Hartlén et al. 19967). The mining waste from lead and zinc mines was used in bituminous mixtures for road materials. According to a systematical analysis of material behavior, tailing soil mixed with coal fly ash was reused to road construction (Andrei et al. 1998). Hanna et al. (1998) also tried to apply the industrial wastes-soil mixture to road base course and subbase.

3.6 Municipal Solid Waste Incinerator Ash (MSWIA)

Municipal solid wastes (MSW) are often incinerated by the intermediate treatment facilities, and as the result, bottom ash and fly ash are discharged from incinerators and most of them are disposed of in landfill sites. Since harmful substances (heavy metals, dioxins, etc.) are being concentrated and compounded during incineration process, MSW incinerator ash (MSWIA) must be carefully treated prior to its disposal and thus prevent environmental pollution. In the present system of incinerators, MSWIA is mixed with the bottom ash, which is less harmful. However, MSWIA should be collected separately from bottom ash, and prior to the
disposal, fly ash must be treated as harmless substances by a method of melting, cement hardening, the addition of a chemical agent, or extraction. The use of MSWIA is thoroughly discussed by the International Ash Working Group (IAWG) (1994).

The melting method is considered to be the most effective option because of both reduction of volume and toxicity. However, the method cannot achieve resource recovery in spite of its demand for high cost and energy (Hiraoka and Sakai 1994). Properties of slag depend on types of melting furnace, and heavy metal concentrations of leachate are generally negligible. The slag could be applicable for structural fill and pavement (Nagasaka et al. 1996).

Solidification by cement hardening has been thought of as another recommended method (Shimaoka and Hanashima 1994). In the case of solidification in Japan, government requires that the cement mixing ratio is more than 150 kg/m\(^3\) and the compressive strength is higher than 10 kgf/cm\(^2\) (980 kPa).

The properties of MSWIA depend on the type of incinerator, temperature, and raw materials used. The incinerator from which the fly ash was collected was a fluidized combustion type whose incineration temperature was in the range of 800-1000 degrees in Celsius. The chemical composition and leachate components of the MSWIA are shown in Table 7. Cd, Pb, and Zn leach in high concentration from the used ash, which can not satisfy the environmental criteria established for landfilling by the Environmental Agency of Japan. Another important characteristic of the materials is the salt contents. MSWIA consists of high composition of NaCl and KCl.

According to the testing results of strength characteristics for the stabilized MSW fly ash, MSW fly ash stabilized by FCA has higher strength than the fly ash stabilized by other stabilizers in each additive content and curing period.

The leachate behavior of heavy metals such as Cd, Pb, and Zn, contained in the MSW fly ash were examined and kept at low levels. The multiple use of cement and FCA as a MSWIA stabilizer can attain strength development, high soaking durability, and the containment of heavy metals. The method is effective for landfilling with MSWIA.

Research has been carried out on the geotechnical utilization of MSW bottom ash (e.g., Hartlén 1994, Hartlén and Flyhammar 2000, Almeida et al. 1998, Luz and Almeida 1998, and Nabeshima and Matsui 1998). Research on the utilization of MSW fly ash as a construction material has been conducted recently in the US and Europe (e.g., Gerdes and Wittmann 1994). Poran and Ahtchi-Ali (1989) reported that the MSW fly ash in the US contains just a small amount of NaCl and can be stabilized effectively by lime and applied as a road material. However, MSW fly ash usually contains a large amount of salt, which affects the hardening reaction of cement or lime (Kamon 1996). Thus, a more effective method for MSW fly ash solidification is needed from technical, environmental and economical point of view.

Hartlén and Flyhammar (2000) have shown that the release of harmful substances is much more dependent if the bottom ash is placed above or under the groundwater table. Placement under the groundwater causes much less release due to reducing conditions.

### Table 7 Chemical composition and leachate components of MSW fly ash (Kamon 1996)

<table>
<thead>
<tr>
<th>Chemical compositions</th>
<th>Leachate components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cd (mg/kg)</td>
<td>Pb (mg/kg)</td>
</tr>
<tr>
<td>225</td>
<td>3750</td>
</tr>
<tr>
<td>Cd (mg/L)</td>
<td>Pb (mg/L)</td>
</tr>
<tr>
<td>10.4</td>
<td>19.6</td>
</tr>
</tbody>
</table>
Recently, a new treatment system has been developed for MSW, as shown in Fig. 8. All of MSW and sewage sludge are directly melted in the furnace and the produced gas is used to generate electricity. The molten matter is lead to a water pond and made a slag. The molten slag has neither heavy metals nor dioxins. The iron component is collected from the molten slag by magnetic separator. During the whole process, excess energy is introduced to electric generator and heating the regional area. This system has brought an almost perfect recycling of MSW. The final disposal volume at the end of this system decreased to less than 1% of the raw MSW.

3.7 Sewage Sludge Incinerator Ash

Several types of waste sludge are generated from industry. The most common is sewage sludge. In order to reduce the volume of sludge, incineration is used as a representative intermediate treatment. Sewage sludge incineration ash (SSIA) is divided using lime and polymer flocculants. SSIA separated by lime flocculant can be used as subbase, filling and embankments. This ash has similar characteristics to sandy soil, as well as hygroscopic and hardening properties due to its lime content. On the other hand, SSIA separated by polymer flocculant is similar to clay soil, and is used only as subgrade and subbase. Bricks made from this ash have been tried as a substitute for clay materials. Almeida et al. (1998) also reported the applicability of sewage sludge to a ceramic material mixed with sawdust.

Various processing methods have been researched for sludge utilization. One involves production of molten slag by melting. Slag made from sewage sludge is suitable for use as construction material and is compatible with the environment. Its use as interlocking blocks has been established (Iwai et al. 1987).

Another method involves SSIA to produce hardening material. It has been proposed that the material generated by combining industrial waste sludge with lime, can be used for soil stabilization (Kamon and Nontananandh 1991). The proposed stabilizing agent (NCS) works as well as the ordinary Portland cement, as shown in Fig. 9. These methods are acceptable from the environmental and geotechnical point of view but pose economic problems. The use of stabilizers and/or additives, such as cement-based-stabilizer or clays, produces materials which are applicable for subbase, subgrade and embankment.
3.8 Paper Sludge

Recent studies proposed that paper sludge (PS), the residues from wastewater treatment plants at paper mills, can be used as a hydraulic barrier layer in landfill covers (Kraus et al. 1997, Moo-Young and Zimmie 1996, Quiroz and Zimmie 1998, Saarela 1999, Rajasekaran et al. 2000). The key properties of PS are high water content (150-270%), high organic content (35-55%), high compressibility, and low hydraulic conductivity, as listed in Table 8, and the engineering properties of PS are similar to those of the organic soils. Low hydraulic conductivity values can be achieved over the wide range of water content, either wet or dry of optimum water content (Kraus 1997, Moo-Young and Zimmie 1996), unlike the compacted clays which require the relatively strict compaction criteria (Benson et al. 1999). In addition, the hydraulic conductivity decreases with time due to consolidation phenomena (Rajasekaran et al. 2000). Fibers remained in the PS have an excellent effect on gaining the strength and stability against the differential settlement that might occur for the cover material (Moo-Young and Zimmie 1996). High resistance of PS against the frost action was also reported by Kraus et al. (1997). These properties promise the application of PS to a hydraulic barrier material in the landfill cover system. In US, the barrier layer in landfill cover systems is required to have a hydraulic conductivity smaller than or equal to $10^{-5}$ cm/s for municipal solid waste landfill, and $10^{-7}$ cm/s for hazardous waste landfill. Many PSs reported meet these criteria to be used as a hydraulic barrier.

3.9 Waste Tires

Scrap tires are the industrial wastes produced at increasing rates every year. It is estimated that approximately 10 million used tires are annually generated in Japan. The United States disposes of approximately 50 million tires into landfills, while 30% of the waste tire production (28 million) is estimated
to be disposed in waste landfills or tire stockpiles in Canada (Garga and O’Shaughnessy 2000). Although more than 90% of used tires produced in Japan are recycled as rubber material, used as the solid fuel in cement kiln, or reused as tire (Nagasaka et al. 1996), further applications for recycling these scrap tires should be established to ensure using large quantities of the material.

For geotechnical applications, scrap tires are used in three different shapes, namely (1) shredded tires, (2) ground tires, or (3) raw tires. Since tires are composed of the carbon-based rubber materials, they usually exhibit low specific gravity, adiabatic properties, and sorbability to organic chemicals. In addition, the shredded tires exhibit excellent frictional properties. Thus, several applications have been proposed to reuse these scrap tires.

Frictional properties of shredded tires result in the increase of soil strength by reinforcement, and consequently use of the shredded tire-soil mixture can be encouraged. (e.g., Foose et al. 1996). In addition, because of their lower specific gravity, shredded tires can be utilized as an light-weight and strong fill materials for earthen structures (Bosscher et al. 1997, Humphrey et al. 1998, Garga and O’Shaughnessy 2000). Further, they are proposed to be used in embankments over soft ground or as backfill behind retaining structures (e.g., Bosscher et al. 1997). Edil and Benson (1998) summarized that tire chip-sand mixtures

---

Fig. 10 Example of embankment construction using non-shredded tires (Schlosser et al. 1994)
exhibit non-linear plastic deformation under the one-dimensional compression condition, while the behavior under the repetitive loading is essentially linear after the first cycle of loading. Therefore, the behavior of tire chip-sand mixture can be approximated with an elastic model. Field demonstration by using a test embankment reported by Bosscher et al. (1997) proved this approximation.

Several researchers proposed to use the non-shredded tires for embankment and fill materials (Schlosser et al. 1994, Long 1996, Garga and O’Shaughnessy 2000). In France, this application method has been well-known as “Pneusol – Tyresoil.” The tires tied together by straps, and assembled into layers as shown in Fig. 10. Long (1996) reported the field demonstration of a 5-m-high wall having the Tyresoil as backfill materials in 1992, and more than 500 structures have been constructed by using Pneusol in France due to several advantages of this application (speed of execution, etc). Extensive study by Garga and O’Shaughnessy (2000) indicated that non-shredded tire fill exhibits ease of construction, but higher compressibility relative to the conventional fill material, and proposed a method of designing the tire-reinforced slopes.

Because the tire is composed of rubber, it may exhibit higher adiabatic properties relative to the soil. Thus, backfilling using tire chips was proposed to prevent the frost heaving of irrigation and drainage channel in cold regions (Nagasaka et al. 1996). From a field demonstration, backfill of the waste tire chips (< 50 mm in diameter) behind the channel kept the 2-degree-higher ground temperature than the conventional backfilling.

Carbon-based rubber material, of which the tire is mainly composed, is a highly sorbent material. Therefore, several methods are proposed to use the shredded or ground tires as inexpensive sorbents. Shredded tires can be used as a leachate collection layer above landfill liners, as a reactive layer for leachate treatment or other similar applications (Kim et al. 1997). Ground tires can also be mixed into sand bentonite slurry walls to enhance their attenuation ability (retardation factor) against organic chemicals (Park et al. 1996). Park et al. (1996) proposed that the incorporation of ground tire into slurry wall may result in the significant delay in breakthrough time for organic compounds, or decrease the design thickness of SB wall.

3.10 Waste Plastics and Other Similar Materials

Waste plastics are difficult to treat and dispose of. Waste plastics are generated as both industrial and municipal waste. Some of waste plastics are reused as a fuel by gasification and oilification. Some kinds of waste plastics are effectively used for asphalt aggregate of road pavement (Yamada and Inaba 1993). For example, Fig. 11 exhibits that the dynamic stability of asphalt mixture is improved by the incorporation of waste plastic pieces.

Expanded polystyrene (EPS) is used at most twice or three times. Small pieces of waste EPS are mixed with soil and cement and utilized in lightweight embankment materials (Yamada et al. 1989).

Waste oils are mainly reused as fuels as far as the viscosity of waste oils is not so high. The high viscous waste oil is one of the most difficult materials to reuse. Sawa et al. (1994) reported that high viscous waste oil can be stabilized using industrial wastes such as sludge incineration ash or iron slag with stabilizers, and then reused for ground materials.

![Graph of Dynamic stability of asphalt mixture with waste plastics (Yamada and Inaba 1993)](image-url)
4.0 ENVIRONMENTAL SUITABILITY ASSESSMENT

4.1 General Concept of Risk Assessment

To be able to re-use waste material, the quality both regarding physical and environmental properties have to be proven. To justify re-use, the decision basis shall be related to a profound risk assessment. Primarily, the risk shall be based on a combination of a probability that a damage and a consequence of the damage will occur. The probability is related to factors as volume used, potential for leaching harmful substances transferred to the actual situation/environment and concentrations at target points in soil and water.

Today, no such general system exists based on relevant risk assessments. In most cases, the assessments are related to concentrations accepted by authorities developed for other applications, as drinking water standard or acceptable change in concentration in surface water. The Swedish Environmental Protection Agency (Naturvårdsverket) has in 1999 issued a report on contaminated soil, where a methodology is presented on how to make the rating. A similar approach could be relevant to utilisation of residues.

In many countries, work is proceeding to develop decision criteria when and how to use secondary materials (Hartlén et al 1999b). Activities in the Netherlands and Denmark have developed such systems to specific residues. In EU, work is going on giving standards to waste disposal where the waste is divided into different classes based on their hazardous level. CEN is in parallel working with leaching of materials in TC 292.

The risk assessment of the use of secondary materials in constructions is composed of several parts as follows.

*Problem formulation*

The aim is to identify the hazardous properties and substances in the material that are relevant in the scenario and to identify the pathways and target points for these substances. This is equivalent to step 1-3 in ENV 12920 “Methodology for the determination of the leaching behavior of waste under specified conditions”.

*Description of the material*

The residue needs to be described (Step 3, ENV 12920) and the relevant substances for the risk assessment should be selected. The description of the waste needs to consist of:

- identification of the physical properties
- identification of the hazardous properties in relation to Council directive on hazardous waste 91/689/EEC
- identification of the composition of the material in relation to inorganic and organic substances.

*Description of the scenario*

The application/scenario shall be described in detail in relation to the actual construction and to the local environment (Step 2 ENV 12920). The description of the scenario shall include:

- geotechnical conditions
- hydrogeological conditions
- biological conditions
- use of the site over time
- exceptional conditions

*Selection of target substances and target points*

Based on the description of the residue, the target substances are selected. Several target points will be identified based on the description of the scenario and shall be selected in regard to all relevant exposures to mankind and nature. The pathways addressed in the transport model shall give concentration or exposures of the target substances at the identified target points.

*Exposure assessment*

The exposure assessment consists of two parts: transport of target substance from source to target point and evaluation of the sensitivity to environmental hazards of the area included in the scenario.

*Risk evaluation*

The risk evaluation consists of the step, where the calculated exposures and concentrations at the target points are compared to different already set up quality criteria.
Risk management

There is a need for a general statement from the authorities on which level of effect is acceptable.

To outline this risk assessment procedure, it is obvious that several important areas need further development before the system can be fully implemented. In this context, different tools need also to be developed.

The outlined system for risk assessment as above, shall be regarded as the basic system, which however may not be easy to use on a regular basis. Simplifications are thus needed to obtain a system that is useful in practice. Different applications may also need applied quality assurance systems.

4.2 Leaching of Toxic Chemicals from Recycled Materials

When utilizing the recycled materials, such as industrial and municipal wastes and surplus soils, the potential for pollution caused by these materials has to be assessed under the environment of a given application. Table 9 summarizes the potential of pollution by toxic chemicals contained in the wastes, with respect to treatment methods and applications. Surplus soils and waste sludges from earthen works may not have a risk for pollution since they do not contain toxic chemicals. Without proper treatment, most types of industrial wastes (coal ash, slag, scrap tire) may have a toxicity potential. MSW incinerator ashes have a risk for pollution since they do not contain toxic chemicals. Without proper treatment, most types of industrial wastes (coal ash, slag, scrap tire) may have a toxicity potential. MSW incinerator ashes have a risk for pollution since they do not contain toxic chemicals. Without proper treatment, most types of industrial wastes (coal ash, slag, scrap tire) may have a toxicity potential.

To estimate the in-situ environmental suitability, leaching potential of the toxic chemicals has to be evaluated. To outline this risk assessment procedure, it is obvious that several important areas need further development before the system can be fully implemented. In this context, different tools need also to be developed.

There is a need for a general statement from the authorities on which level of effect is acceptable. The outlined system for risk assessment as above, shall be regarded as the basic system, which however may not be easy to use on a regular basis. Simplifications are thus needed to obtain a system that is useful in practice. Different applications may also need applied quality assurance systems.

Table 9 Potential for pollution with respect to treating grade and application

<table>
<thead>
<tr>
<th>Treatment method</th>
<th>Leachant</th>
<th>pH (initial)</th>
<th>pH = 3.8-6.3 (fixed)</th>
<th>pH = 7 and 4.9 (fixed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-treatment</td>
<td>DW</td>
<td>2.0-4.9</td>
<td>DW + HCl</td>
<td>DW + HNO₃</td>
</tr>
<tr>
<td>Crushing</td>
<td>DS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Screening</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aggregating</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solidification</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combustion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 10 Regulatory leaching tests in several countries

<table>
<thead>
<tr>
<th>Test Type</th>
<th>TCLP Method 1311 EPA</th>
<th>DIN 38414 •DEV-S•</th>
<th>AFNOR X31-210 Leaching test</th>
<th>JLT-46 Leaching test</th>
<th>NEN 7341 Availability test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country</td>
<td>USA</td>
<td>Germany, Austria, Belgium</td>
<td>France</td>
<td>Japan</td>
<td>Netherlands</td>
</tr>
<tr>
<td>Particle size</td>
<td>&lt; 9.5 mm</td>
<td>&lt; 10 mm</td>
<td>&lt; 4 mm</td>
<td>&lt; 2 mm</td>
<td>&lt; 125 μm</td>
</tr>
</tbody>
</table>

Table 11 Composition of construction materials in the Netherlands (Building Materials Decree, Netherlands, 1996)

<table>
<thead>
<tr>
<th>Composition</th>
<th>Special Category MSWI - BA (isolation measures required)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WSC</td>
<td>Waste concrete, powder, cement, or rotation Shaking table or rotation Stirrer</td>
</tr>
<tr>
<td>WRC</td>
<td>Waste rock powder, cement, or rotation Shaking table or rotation Stirrer</td>
</tr>
<tr>
<td>WC</td>
<td>Waste cement, or rotation Shaking table or rotation Stirrer</td>
</tr>
<tr>
<td>WS</td>
<td>Waste soil, or rotation Shaking table or rotation Stirrer</td>
</tr>
<tr>
<td>CP</td>
<td>Coal product, or rotation Shaking table or rotation Stirrer</td>
</tr>
<tr>
<td>MSWIA (C, X)</td>
<td>Municipal solid waste incinerated ash, or rotation Shaking table or rotation Stirrer</td>
</tr>
</tbody>
</table>

Note: A: Non-toxic (raw material); X: Sometimes toxic (treated material); Y: Toxic (treated material)
assessed. There are various elution test methods, and even regulatory methods vary with countries, as shown in Table 10. Most of the elution tests regulated in the US, Japan, and European counties require the materials to be crushed or ground, mixed with water (either, neutral or acid), agitated, and filtered for chemical analysis. Recently, numerous discussions have been conducted on this topic (e.g., Hartlén et al. 1997, IAWG 1997, Kamon 1998). One of the problems pointed out is that most elution tests reflected under only one pH condition (in particular, although many ashes exhibit alkali), and do not consider the given environment for the applications or the possible highest risk. The pH dependent leaching test, which evaluates the leaching characteristics with a wide range of pH value, reveals that the containing heavy metals may leach out in a large quantity of solution under the special condition of pH values.

In addition to the leaching value, composition value of the toxic chemicals is also a key factor. For example, in the Netherlands, a comprehensive program has been implemented to set standards for the use of primary and secondary construction materials (Building Materials Decree, 1996). The standards are based on emission and composition values, and construction materials are divided into two categories as shown in Fig. 12. Materials in Category 1 can be used without restriction, while residue in Category 2 may be used under a certain isolation measures. Even if the leaching amount satisfy the level for Category 1, the materials exceeding the certain amount in composition value are prohibited to be used as construction materials, because they may have a potential for pollution in the future. Besides the composition value, availability test standardized also in the Netherlands is used to evaluate the maximum potential of leaching mass from the materials, where materials have to be crushed and ground into the powders smaller than 0.125 mm in particle size, and stirred with the water under the acid condition (pH = 4) is kept.
Although batch leaching tests listed Table 10 require that the sample is crushed into particles, they are not representative of in-situ conditions of the recycled materials, in particular for the stabilized waste. Column and tank leaching tests were used to determine the leaching amount of non-crushed material. Kamon and Katsumi (1999) and Kamon et al. (2000) reported that the stabilized soil containing heavy metals may be used in geotechnical applications from the column leaching test, while the batch leaching test results do not allow the utilization of same material based on the environmental standards. On the contrary, leaching amount from the column leaching test sometimes exceeds the leaching amount from the availability test, which is used to estimate the maximum potential of leaching (Kamon et al. 1999).

Another problem regarding the leaching tests is the accuracy. Higaki et al. (1999) reported the leaching test results on MSW fly ash, sewage sludge incinerator ash, and coal fly ash. The tests were conducted on the same samples at four different organizations. The results shown in Tables 11 and 12 indicated that the leaching amounts vary with the organizations. It is considered that the level of the leaching amount is a very small quantity such that the several undesirable factors during elution and determination procedures may result in inaccuracy. We, geotechnical engineers, have to improve our skills for the chemical analysis!

<table>
<thead>
<tr>
<th>Substance</th>
<th>MSW</th>
<th>SSMS</th>
<th>CFA</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>36.5</td>
<td>26.2</td>
<td>48.7</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>19.7</td>
<td>14.6</td>
<td>32.9</td>
</tr>
<tr>
<td>CaO</td>
<td>25.3</td>
<td>24.1</td>
<td>6.20</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>6.34</td>
<td>9.42</td>
<td>5.59</td>
</tr>
<tr>
<td>TiO₂</td>
<td>1.80</td>
<td>0.71</td>
<td>1.59</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>2.55</td>
<td>17.8</td>
<td>1.40</td>
</tr>
<tr>
<td>K₂O</td>
<td>1.46</td>
<td>1.72</td>
<td>1.10</td>
</tr>
<tr>
<td>SO₃</td>
<td>0.35</td>
<td>1.06</td>
<td>0.94</td>
</tr>
<tr>
<td>MgO</td>
<td>4.04</td>
<td>2.96</td>
<td>0.80</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.62</td>
<td>-</td>
<td>0.11</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>0.18</td>
<td>0.15</td>
<td>0.08</td>
</tr>
<tr>
<td>PbO</td>
<td>0.001</td>
<td>-</td>
<td>0.05</td>
</tr>
</tbody>
</table>

MSW; Municipal solid waste fly ash
SSWS; Sewage sludge ash
CFA; Coal fly ash

<table>
<thead>
<tr>
<th>Waste</th>
<th>Toxic substance</th>
<th>Organization A</th>
<th>Organization B</th>
<th>Organization C</th>
<th>Organization D</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSW Prototype</td>
<td>Pb 0 0 0 0.025</td>
<td>Cr^{6+} 0 0 0</td>
<td>As 0 0 0 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 100μm</td>
<td>Pb 0 0 0 0.023</td>
<td>Cr^{6+} 0 0 0</td>
<td>As 0 0 0 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SSMS Prototype</td>
<td>Pb 0 0 0 0.027</td>
<td>Cr^{6+} 0 0 0</td>
<td>As 0 0 0 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 100μm</td>
<td>Pb 0 0 0.001 0.017</td>
<td>Cr^{6+} 0 0 0</td>
<td>As 0 0 0 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CFA</td>
<td>Pb 0 0.038 0 0.012</td>
<td>Cr^{6+} 0.04 0.037 0.002 0</td>
<td>As 0 0 0 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 100μm</td>
<td>Pb 0 0 0 0.01</td>
<td>Cr^{6+} 0 0.002 0.009 0</td>
<td>As 0 0 0 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cement solidification</td>
<td>Pb 0 0 0 0.01</td>
<td>Cr^{6+} 0 0.002 0.009 0</td>
<td>As 0 0 0 0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Several field demonstrations were reported, for example, on steel slag by Fällman and Hartlén (1996) and on scrap (un-shredded) tire embankment by O’Shaughnessy and Garga (2000). Fällman and Hartlén (1996) installed the lysimeter under the test road of steel slag, and the collected seepage was analyzed to determine the concentration of leached heavy metals. They reported that the leaching amount from the field test road exhibit the similar values of leaching amount from the laboratory column leaching test if the test results are plotted with L/S (liquid to solid ratio), as shown in Figs. 13 and 14. Another interesting point from their field demonstrations is that large leaching amount of vanadium occurred from the screened slag (particle size > 11 mm) than un-screened slag, while the leaching of lead from screened slag is larger than unscreened slag. Fällman and Hartlén (1996) concluded that pH values have a significant effect on leaching characteristics of metals. O’Shaughnessy and Garga (2000) reported no significant leaching occurred from the non-shredded tire embankment.

4.3 Leaching of Chromium from Cement-Stabilized Materials

Solidification techniques by using cement, lime, or other agents are sometimes used to stabilize the waste materials to attain the suitable properties for the geotechnical applications. One of the purposes to use cement was previously considered to immobilize the toxic chemicals contained in the waste. However, it was recently revealed that Portland cement may have a risk of leaching of six-valent chromium (Cr\textsuperscript{6+}). Kamon (2000) reported that the ordinary Portland cement normally contains chromium in the range of 30 to 100 mg/kg. The chromium is originally included in raw materials of cement. Table 13 shows an example of the chromium contents in the raw materials. Among the raw materials, not only slags, but also limestone and silica, that are...
natural products, contain a significant amount of chromium. When these raw materials are sintered in the cement kiln, they are oxidized to six-valent chromium. From the leaching tests, a considerable mass of Cr\(^{6+}\) was detected from the cements supplied by the several Japanese cement manufacturers, as summarized in Table 14. This result means that a careful attention must be paid to prevent the environmental risk when the cement is used. The Japanese environmental standard of the Cr\(^{6+}\) leachate is below 0.05 mg/L, and six-valent chromium leaching from cement itself may have a high risk to contaminate the surrounding environment, i.e. groundwater. Leaching tests for the cement-stabilized soils were also conducted to clarify the level of contaminating risk by cement stabilized materials. As shown in Table 15, Cr\(^{6+}\) leachate from the cement-stabilized soils was significant, and it depends on the type of soils to be treated. In the case of alluvial clay soils, Cr\(^{6+}\) leachate was not significant, while leaching concentrations from the sand and/or loam soils stabilized with cement were significantly high. The additive content of cement, of course, affected the leachate volume. Due to these facts, the Japanese Ministry of Construction recently established a requirement regulation for all Japanese contractors to provide the environmental guarantee by conducting leaching tests, which must be performed prior and after the execution of cement stabilization.

4.4 Alkaline leachate

Alkaline leachate is another possible environmental risk that may be caused by the cement and lime stabilization, and may occur under various geo-environmental conditions (e.g., Amano and Matsumoto 1980; Kitsugi 1989; Kamon and Katsumi 1994c, Kamon 1998). Because stabilized materials are surrounded by natural soils, alkaline leachate is expected to be buffered and neutralized by the buffer capacity of these soils. Degree of the buffer varies with soil type. Soils containing finer particles can work much better than coarser particle soils to neutralize alkaline leachate (Miki et al. 1998). From an experimental study in which a lime column was installed into soft clay ground, the area of 10-30 cm far from the stabilized column exhibited high pH, while the pH of the clay soil more than 30 cm far from the column was not affected by the alkaline leachate. Since the sandy soils have low alkaline neutralizing capacity, solidified waste should not be in direct contact with groundwater. Unlike the sandy soil, clayey soil was found to be a filtration layer/cover of the stabilized soil to minimize the alkaline migration because of the high alkaline buffer capacity. However, the clayey soil is not always considered to be suitable for the filtration layer because it is difficult to construct the compacted layer. Besides, alkaline migration and its control from the stabilized materials are strongly affected not only by the individual properties of the stabilized layer and the cover for filtration but also by the combination of these properties. Figure 15 shows a typical cross section utilizing the stabilized waste materials in

![Fig. 15 Water flow around the stabilized soil embankment (Kamon et al. 1996)](image)

geotechnical application; application of the stabilized surplus soil to embankment (Kamon et al. 1996). Kamon et al. (1996) estimated the minimum thickness of the filtration layer beneath the stabilized-soil embankment to prevent the adverse effect through the parametric analysis.
5.0 CONCLUSIONS

The present state of waste management and utilization as well as the methodology to control the environmental risk assessment were discussed in detail. Many technical methods for reuse of wastes have been successfully developed and practically applied. Environmental impact evaluation is essentially important to reuse waste materials for the geotechnical construction works. Social attitudes, industry preconceptions, lack of information network between waste generation sites and reuse sites, economic concerns, etc. still prevent many wastes apart from being utilized in construction works. To reorient society towards waste utilization, related data need to be systematically organized, a scientifically based risk assessment tool, legal and tax systems which give economic incentive to waste utilization must be established, and the present system should be improved to be environmental friendly.

6.0 ACKNOWLEDGEMENTS

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7.0 REFERENCES


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